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OPTICAL DATA TRANSMISSION TECHNOLOGY FOR FIXED AND DRAG-ON STS PAYLOAD UMBILICALS

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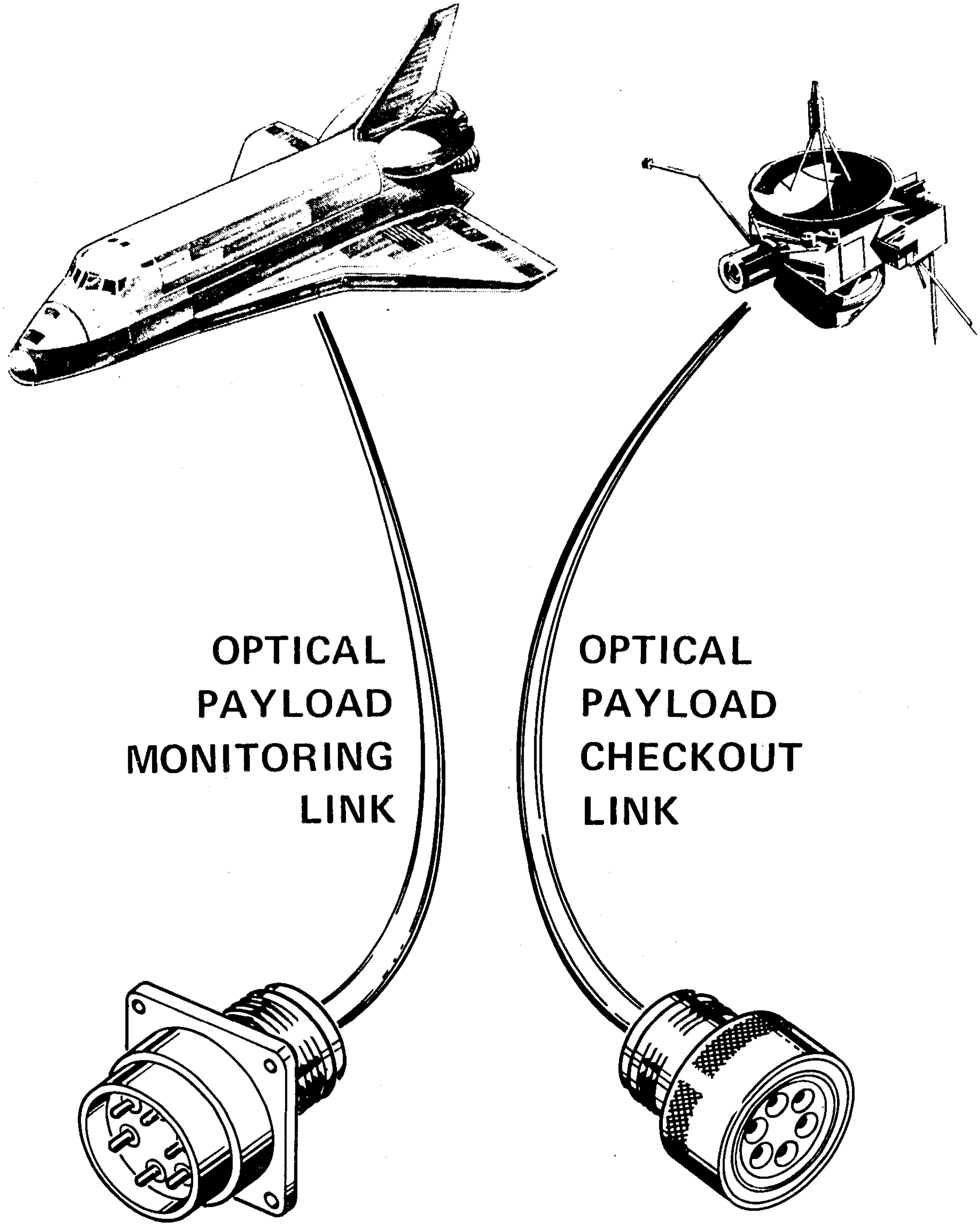
OPTICAL
PAYLOAD
MONITORING
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CHECKOUT
LINK

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1.0 INTRODUCTION

This document is the final report of the Optical Data Transmission Technology for Fixed and Drag-On STS Payload Umbilicals Study under Contract NAS-10-9784 to Kennedy Space Center (KSC). The purpose of this study is to determine if optical data handling methods are applicable to payload communications checkout and monitoring. The study covers both payload umbilicals and interconnecting communication lines carrying payload data. This report includes the following tasks:

- TASK A - Analyze Ground Checkout Requirements
- TASK B - Optical Approach
  1. Technical Survey of Optical Approaches
  2. Selection of Optimum Approach
- TASK C - Survey and Select Components
- TASK D - Compare with Conventional Approach
- TASK E - Define Follow-On Activity

The reason for considering an optical communication approach to checkout and monitor payloads is the numerous advantages of optical transmission. The results of this study show these advantages and the anticipated growth in data communications at KSC to be sufficient reason for employing optical data handling methods to transmit payload telemetry.

One advantage of optical data handling methods over electrical data handling is the higher data rates and bandwidths. Each year optical fiber companies report lower attenuation per kilometer and improved dispersion properties (pulse broadening), implying further increases in bandwidth and data rates. The higher data rates allow for more multiplexing over a single fiber and greater flexibility in upgrading system capacity without the need to install new cables. Open-air laser communications have also achieved data rates in excess of 1 Gigabit/second.

A number of other advantages result from glass fibers and air being an electrically nonconducting media:

- o Optical signals are insensitive to electromagnetic and radio frequency interference, therefore, there is no need for shielding the cables.

- Lightning strikes cannot cause unusually high transients (EMP) in the electronic boxes at either end of an optical link.
- Because optical signals are composed of light and not electricity, they do not contribute to the EMI noise of the environment.
- Electrical transients do not propagate through the system, because optical fibers and air electrically isolate electronic boxes.
- The lack of sparking allows optical cables to pass by flammable and explosive materials (the same property allows small amounts of energy over short distances to be transferred by replacing receivers by solar cells).
- Crosstalk between optical signals can easily be reduced below measurable levels.
- Unlike electrical wires that emit an E-M field, one must break through an optical fiber in order to obtain useful information, resulting in higher security.

2.0 TASK A - REQUIREMENTS ANALYSIS

This section discusses the payload checkout procedure at KSC, data transfer topology, and data rates.

2.1 PAYLOAD CHECKOUT PROCEDURES

Figure 1 shows the sequence of payload processing operations as the payload progresses through individual checkout, integration, installation, and launch.

2.1.1 Payload Processing Facilities (PPF)

Payloads arrive at the Cape/KSC and are transferred to one of the PPFs. The payload contractor checks the individual payload by monitoring the payload telemetry with a direct connection to the GSE equipment collocated at the PPF. Connection is by an umbilical link of less than 200m in length, which is attached either through the test stand or directly to the payload.

2.1.2 Operations and Checkout Building (O&C)

If the payload contains no hazardous materials and the payload contractor requests a horizontal loading, then the payload is transported from the PPF to the O&C building located on Merritt Island. There are four test stands in the O&C building used for the purpose of checking and testing payload telemetry. The payload umbilical link must be capable of transmitting the maximum payload data rate to the ground support equipment (GSE) located in the control rooms. After testing, the payloads to be launched are enclosed in a canister and transported to the OPF.

2.1.3 Orbiter Processing Facility (OPF)

The canister containing horizontally loaded payloads is integrated with the Orbiter at the OPF. Under normal circumstances, as soon as the payloads are integrated into the Orbiter and the interface connections are made, housekeeping and health telemetry from the payload passes through the Orbiter and out through the T/O cables. Data leaving the OPF is transferred to an optical trunk line presently limited to 50 Mb/s. If a payload malfunction is detected, it is possible to attach a payload umbilical directly to the payload. However, it is unlikely umbilical connections are going to be allowed at the OPF;

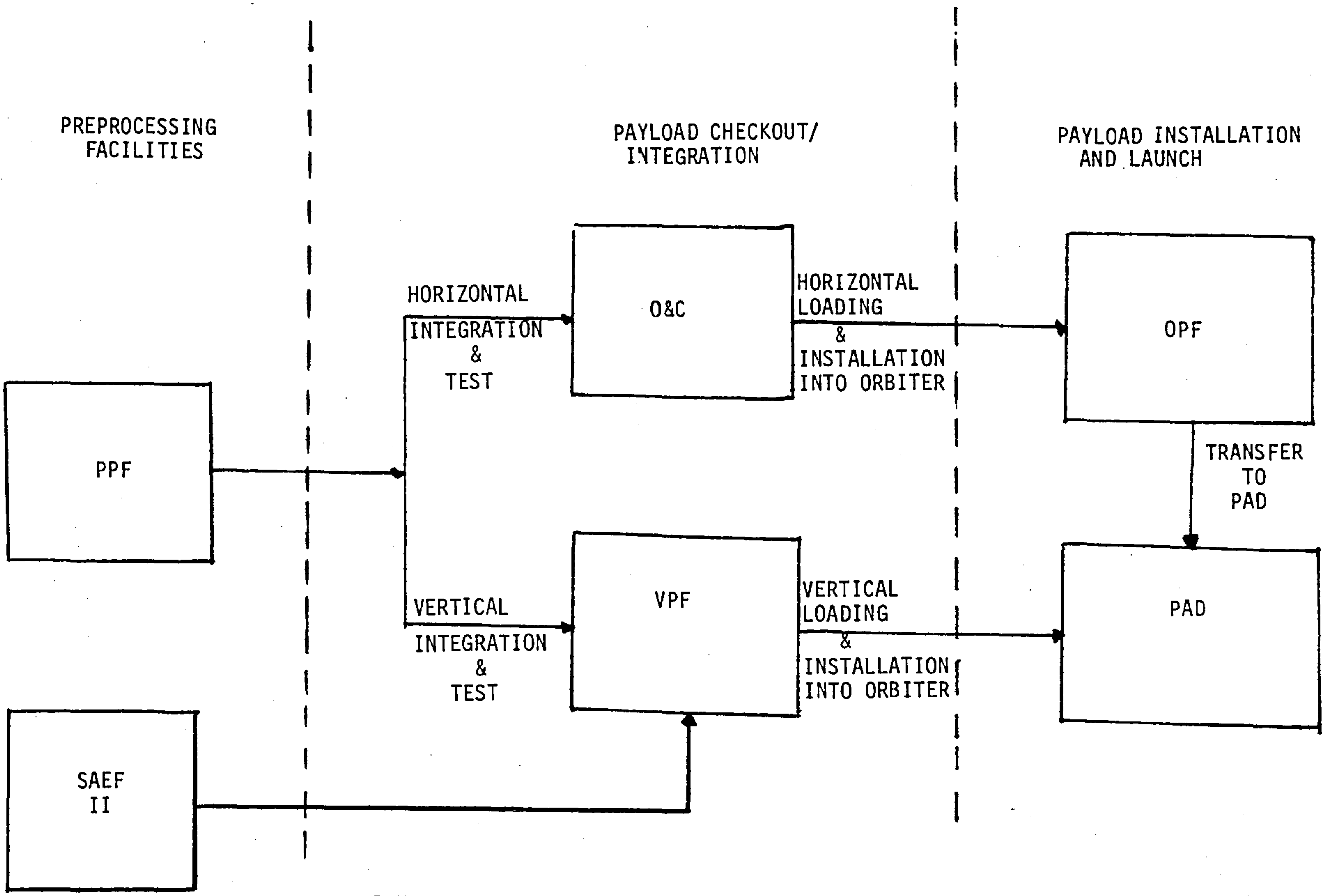


FIGURE 1 FLOW DIAGRAM FOR PAYLOAD PROCESSING

therefore, the payload contractor must move his GSE equipment to the OPF, resulting in a connection similar to the one in the PPF. Once the payloads and Orbiter are operating properly they both move from the OPF to the Launch Pad. The use of drag-on umbilicals within the OPF is considered a rare occurrence because of possible delays in the launch schedule.

2.1.4 Vertical Processing Facility (VPF)

The VPF has a similar function as the O&C building. Payloads are moved from the PPF/SAEF II to the VPF when they contain hazardous materials or the payload contractor requests vertical integration. Again, the payload umbilical link is less than 200 m, but the payload data may be required to be transferred 2.5 Km to the O&C building for checkout verification. A solution to transferring high variable data rates long distances through limited data capacity landlines is discussed in Section 4.3.3. After testing, checkout, and Orbiter interface simulation, the payloads are placed vertically into a canister and transported to the Launch Pad.

2.1.5 Launch Pad

Horizontally-loaded payloads arrive inside the Orbiter and there is no communication with them until the T/O cables are again connected to the Orbiter. Vertically-loaded payloads arrive in a canister at the Launch Pad to coincide with the arrival of the Orbiter and are not tested until integration into the Orbiter and connection of the T/O cables. All payload data is transmitted through the T/O cables, to the Mobile Launch Platform (MLP) and finally through landlines to the LCC. In the event of a payload malfunction, drag-on umbilicals could be used.

2.2 IDENTIFICATION OF PAYLOAD LINK APPLICATIONS

From the above descriptions of the payload processing buildings and the flow diagram, two distinct payload data links can be identified. One communication link is a drag-on umbilical (less than 200 m long) interfacing with either the GSE, or CD&SC, and is normally used in the PPF, O&C, and VPF. It could be used in the OPF and the Pad if needed. This link is referred to, hereafter, as the payload checkout link. The second communication link is used at the

OPF and Launch Pad, and interfaces with optical landlines. This link is referred to as the payload monitoring link.

2.3 DATA CHARACTERISTICS OF THE PAYLOAD COMMUNICATION LINKS

This section covers requirements and limitations of payload telemetry for each of the two communication links.

2.3.1 Payload Checkout Link

The payload checkout link connects the payload to the GSE through a short-haul optical link either directly to the GSE in the O&C or indirectly through a distribution center and the KSC landlines to the GSE equipment at the O&C and VPF.

2.3.1.1 Payload Data Characteristics and Limitations

The NASA Tracking and Data Relay Satellite System (TDRSS), shown in Figure 2, will be used by most NASA satellites during the 1980s. The data rate from future payloads is constrained by the bandwidth of TDRSS to a maximum output of 300 Mb/s.

The NASA End-to-End Data System (NEEDS) Program is developing concepts and demonstrating technology that will have significant effect on the configuration of NASA data systems in the latter part of the 1980s. Various trade-off and optimization studies are planned to be performed within the NEEDS Program prior to recommending the concept for the NASA data system in the 1990-2000 time period. The purpose of the present NASA data system is to provide the capability for the efficient and timely transfer of data from the sensor to the user, to permit the extraction of information by the user.

The NEEDS concept is based on a special data format and the method used to transfer the data through the NASA communication system. Data from payloads, Orbiter, or ground stations is structured into a "packet" along with information regarding the address of the destination, length of useful information, and ancillary information. The packet is entered into an empty time frame of a time-multiplexed communication system and is removed when its destination

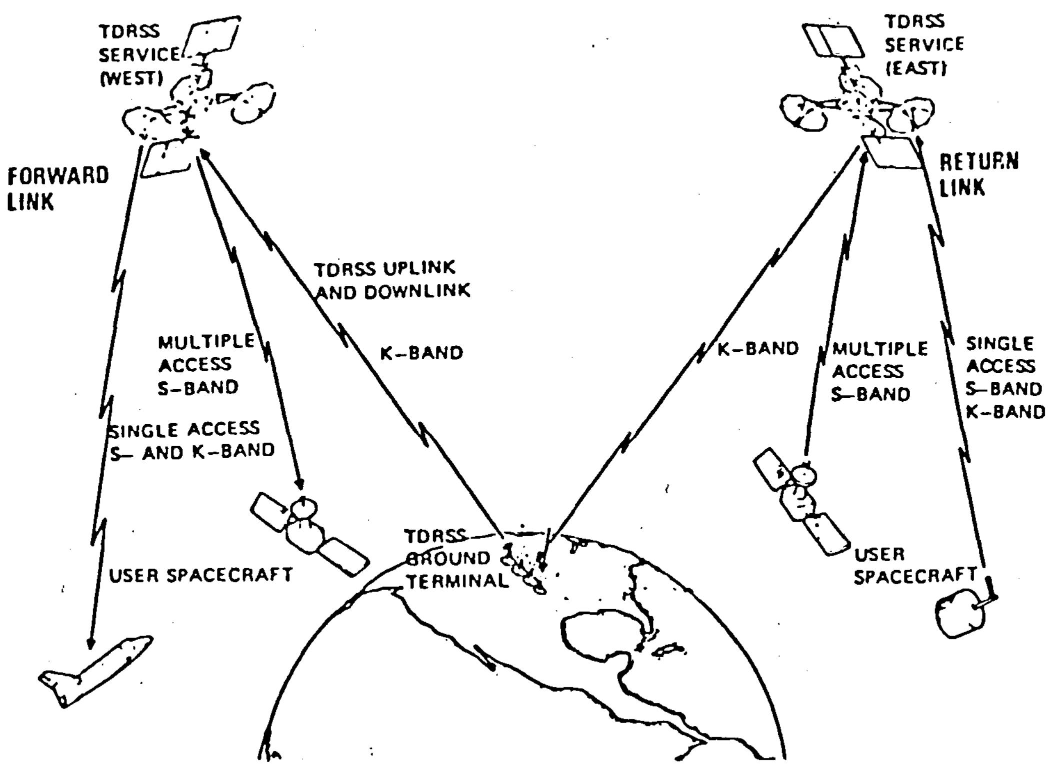
FIGURE 2

TDRSS RF Bandwidth and Data Rates

	Single Access Downlink	Multiple Access Downlink
RF bandwidth	225 MHz	5 MHz
Data Rate	300 Mbps	50 kbps

	Single Access Uplink	Multiple Access Uplink
RF bandwidth	140 MHz	6 MHz
Data Rate	50 Mbps*	10 kbps

*Maximum potential shuttle uplink data rate.



address is correctly identified. Section 5.0 discusses the relationship between the NEEDS concept and the proposed optical communication system.

2.3.1.2 Typical Payloads

Spacecraft can be divided into three categories: attached payloads using the data transmitting facilities of the Orbiter (e.g., Spacelab); free-flyers using the data transmitting facilities of TDRSS (e.g., NOSS, GRO, and ERBE); deep space probes using the data transmitting facilities of the Deep Space Network (e.g., Galileo). The examples in Figure 3 represent typical payloads and do not reach the maximum data rates possible, but these payloads are near-term satellites. It can be anticipated future payloads will grow in transmission capacity until the maximum capacity of the Orbiter (50 Mb/s), TDRSS (300 Mb/s), and Deep Space Network (10 Mb/s) are reached. These are the bandwidth and data rate limitations used for this study.

FIGURE 3

TYPICAL FUTURE PAYLOADS

PAYLOAD	SHORT TITLE	MAXIMUM DATA RATE	DESCRIPTION
EUROPEAN SPACELAB	SPACELAB	50 Mb/s	ATTACHED PAYLOAD
NAVAL OCEANIC SATELLITE SYSTEM	NOSS	4 Mb/s	FREE-FLYER
GAMMA RAY OBSERVATORY	GRO	64 Kb/s	FREE-FLYER
EARTH RADIATION BUDGET SATELLITE	ERBS	32 Kb/s	FREE-FLYER
GALILEO PROBE/ CARRIER	GP	8 Kb/s	DEEP SPACE PROBE

2.3.2 Payload Monitoring Link

This section describes requirements and limitations imposed on the payload data after installation into the Orbiter.

2.3.2.1 General

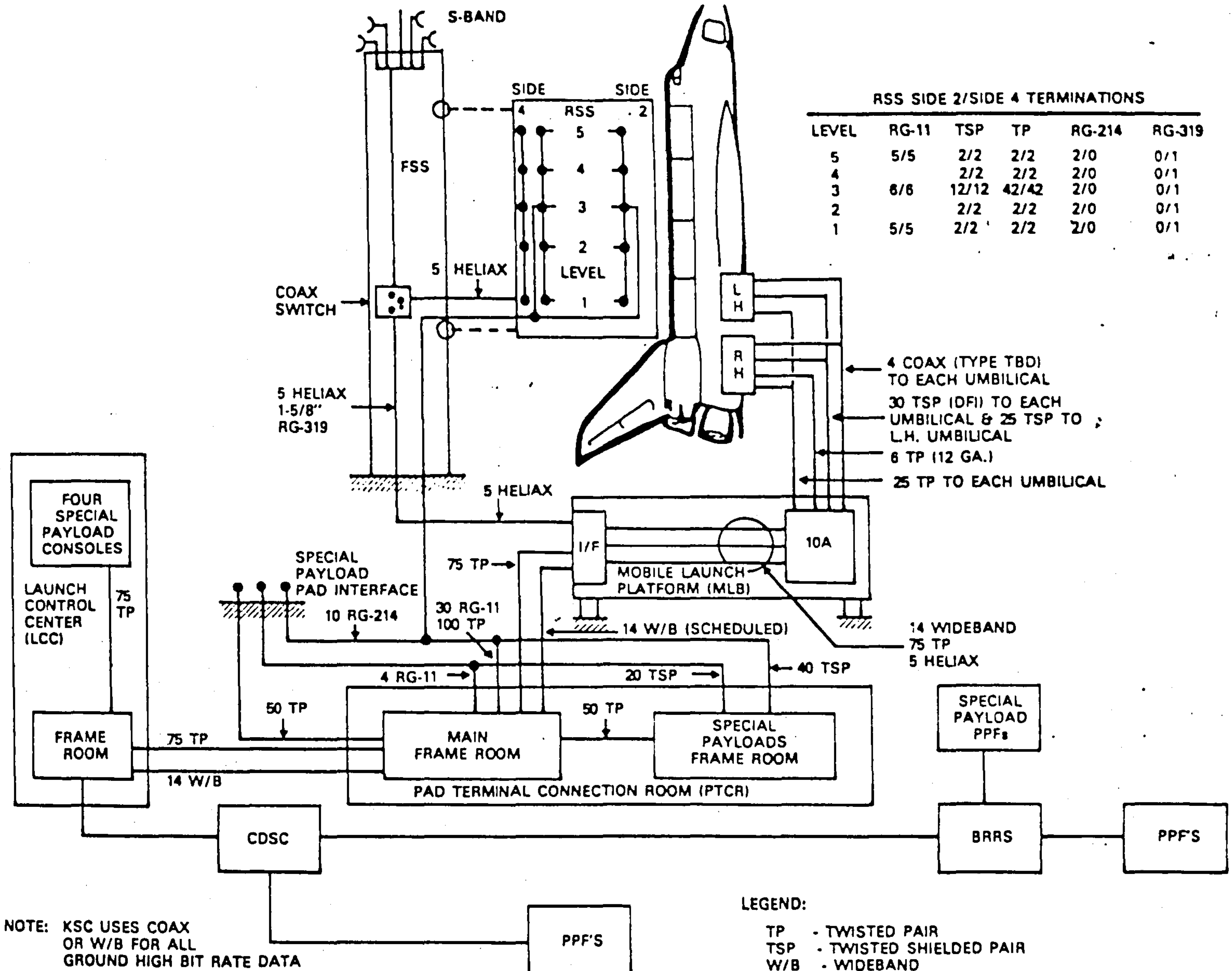
Figure 4 shows the Orbiter/Pad payload cabling interfaces as they exist now. Figure 5 shows the entire communication link, three long-haul cables connecting the Pad with the Communication, Distribution, and Switching Center (CD&SC), and its relationship with the proposed KSC optical cables between the OPF and CD&SC. Figure 9 shows the four short-haul cables starting at the payload, passing through the Orbiter and Mobile Launcher Platform (MLP), and finally terminating in the Pad Terminal Connection Room (PTCR) before interfacing with three long-haul cables. All of the optical sections do not have to be installed at the same time, but no one section can be studied and designed without considering the entire link. The CD&SC was selected as an end point due to its central location for distributing signals.

2.3.2.2 Requirements and Limitations

Data from installed payloads must be transmitted through the Orbiter. Payload data flows through two T/O cables located on either side of the Orbiter; the data rate capacities of these cables are defined by the orbiter/MLP/Pad Interface Document (ICD-2-0A002).

For the OPF, where the payload is installed horizontally into the Orbiter, payload data is transmitted through the T/O cables. Data leaving the payload or Orbiter to another location may be transmitted through the proposed KSC optical link. Presently, this communication link is being studied by another group and is not considered here.

When the payload/Orbiter is located on the Pad, the T/O cables define the data rates being transmitted to the LCC and CD&SC. Due to dispersion (pulse-broadening of signals) and attenuation (light being absorbed by the fiber), it is unrealistic to assume at this time the payload/Orbiter data from the Pad can reach the CD&SC without at least one set of repeaters. If the repeaters are placed at VABR, then optical couplers, must distribute the optical signals into the LCC to avoid a second set of repeaters. If the repeaters are placed at the LCC and there is no distribution of signals at the VABR, the optical signals can be converted to electrical signals and branched into a demultiplexer



RSS SIDE 2/SIDE 4 TERMINATIONS

LEVEL	RG-11	TSP	TP	RG-214	RG-319
5	5/5	2/2	2/2	2/0	0/1
4		2/2	2/2	2/0	0/1
3	6/6	12/12	42/42	2/0	0/1
2		2/2	2/2	2/0	0/1
1	5/5	2/2	2/2	2/0	0/1

NOTE: KSC USES COAX OR W/B FOR ALL GROUND HIGH BIT RATE DATA

LEGEND:

TP - TWISTED PAIR
TSP - TWISTED SHIELDED PAIR
W/B - WIDEBAND
PPF - PAYLOAD PROCESSING FACILITIES
BRRS - BANANA RIVER REPEATER STATION
CDSC - COMMUNICATIONS DIST & SWITCHING CENTER
FSS - FIXED SERVICE STRUCTURE

FIGURE 4 ORBITER-PAD PAYLOAD CABLING INTERFACES

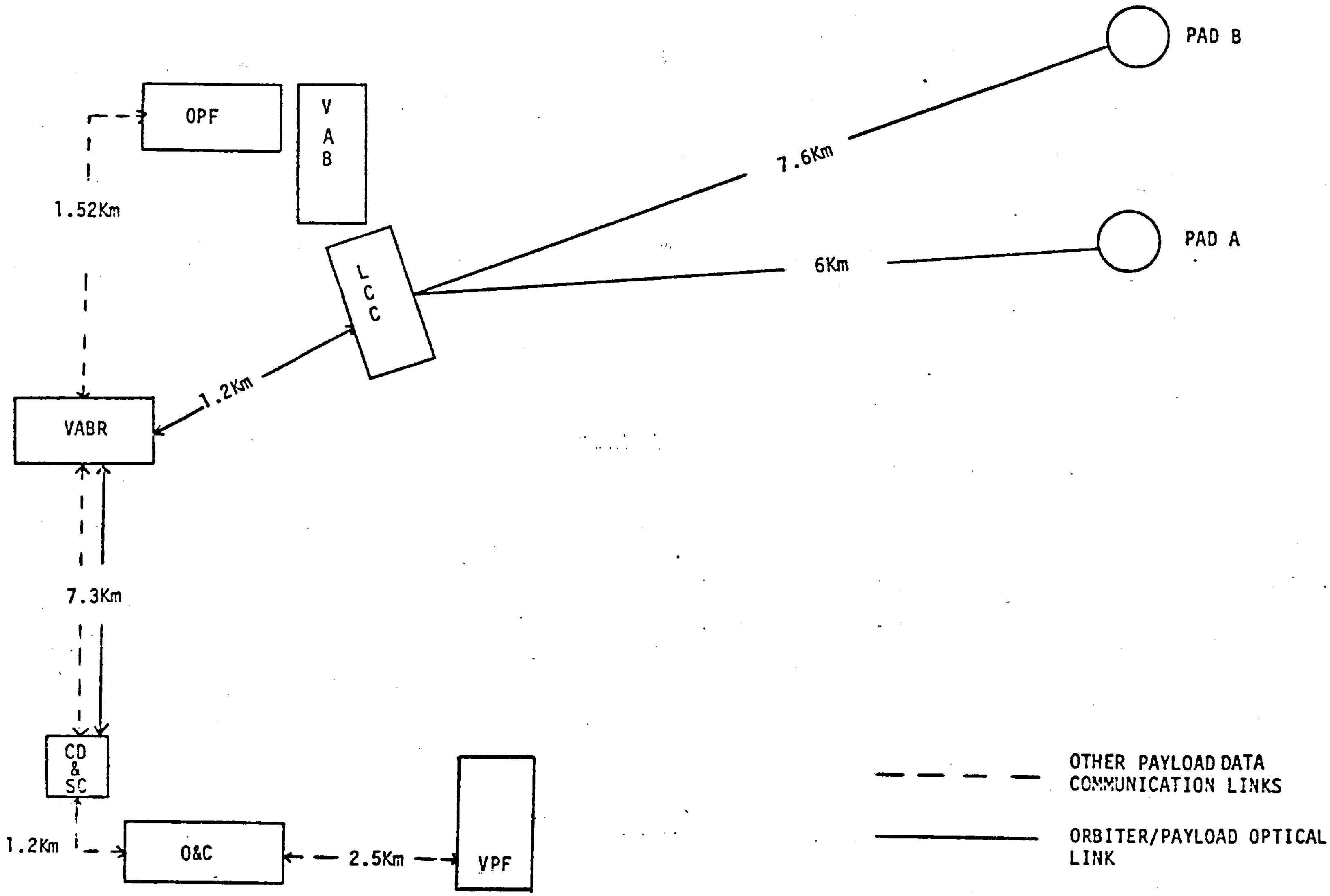


FIGURE (5) - MAP SHOWING DISTANCES OF KSC BUILDINGS TO BE CONNECTED BY OPTICAL LINKS

for the information required at the LCC, and into an amplifier and electro-optical converter to be retransmitted. These new optical signals should have a direct transmission of roughly 9 Km to the CD&SC., Similar equipment and optical components could be used for this link as used in the Pad link.

2.4 CONCLUSION

In summary, the payload checkout link is located in the PPF, O&C, and VPF; it is limited in data transmission to 300 Mb/s, a requirement for payloads using TDRSS. The payload monitoring link is located between the LCC and the Pad; it is limited in data transmission by the T/O cables connected to the Orbiter.

3.0 TASK B - OPTICAL APPROACH

Based on the location of the optical interfaces and the method of optical transmission (glass fiber or air), several optical approaches for the payload checkout link and the payload monitoring link are surveyed. The optimum method of data transmission is selected from the various techniques of multiplexing, modulation, and formating. Finally, the optimum approach for both payload data links is illustrated in a block diagram.

3.1 OPTICAL APPROACHES FOR PAYLOAD CHECKOUT LINK

There are three options for the payload-to-GSE optical link. The location of the electrical-to-optical signal conversion can be: at the test stand, within the connector, and at the payload. A fourth option considers an open-air transmission of payload data using a nonsemiconductor laser.

Option A, shown in Figure 6, puts the electro-optical interface at the test stand. This option requires no modification to the payload since the electro-optic (E/O) interface is at the test stand; presently, this configuration is being designed for use on the European Spacelab. Electrical cables are connected between the payload and the electro-optical (E/O) converters on the test stand, then optical fibers are connected between the E/O converter on the test stand to the O&C data distribution room. Any payload which has not been designed with electro-optical converters could use this method to communicate with its GSE equipment. A standard optical cable having fibers capable of transmitting up to 300 Mb/s and electro-optic converters would be left connected to the test stand. A small box particular to the payload would do the necessary signal conditioning and mating with the E/O unit. If the electrical channels to be converted to optical channels exceed the number of available fibers and E/O converters, then a multiplexer must be used to reduce the electrical channels. This approach can be used for any present and future designed payloads.

Option B, shown in Figure 6, shows the electro-optical interface at the payload. This option assumes that at a future date all payloads will be required to have an optical connector and electro-optical converters. A standard optical

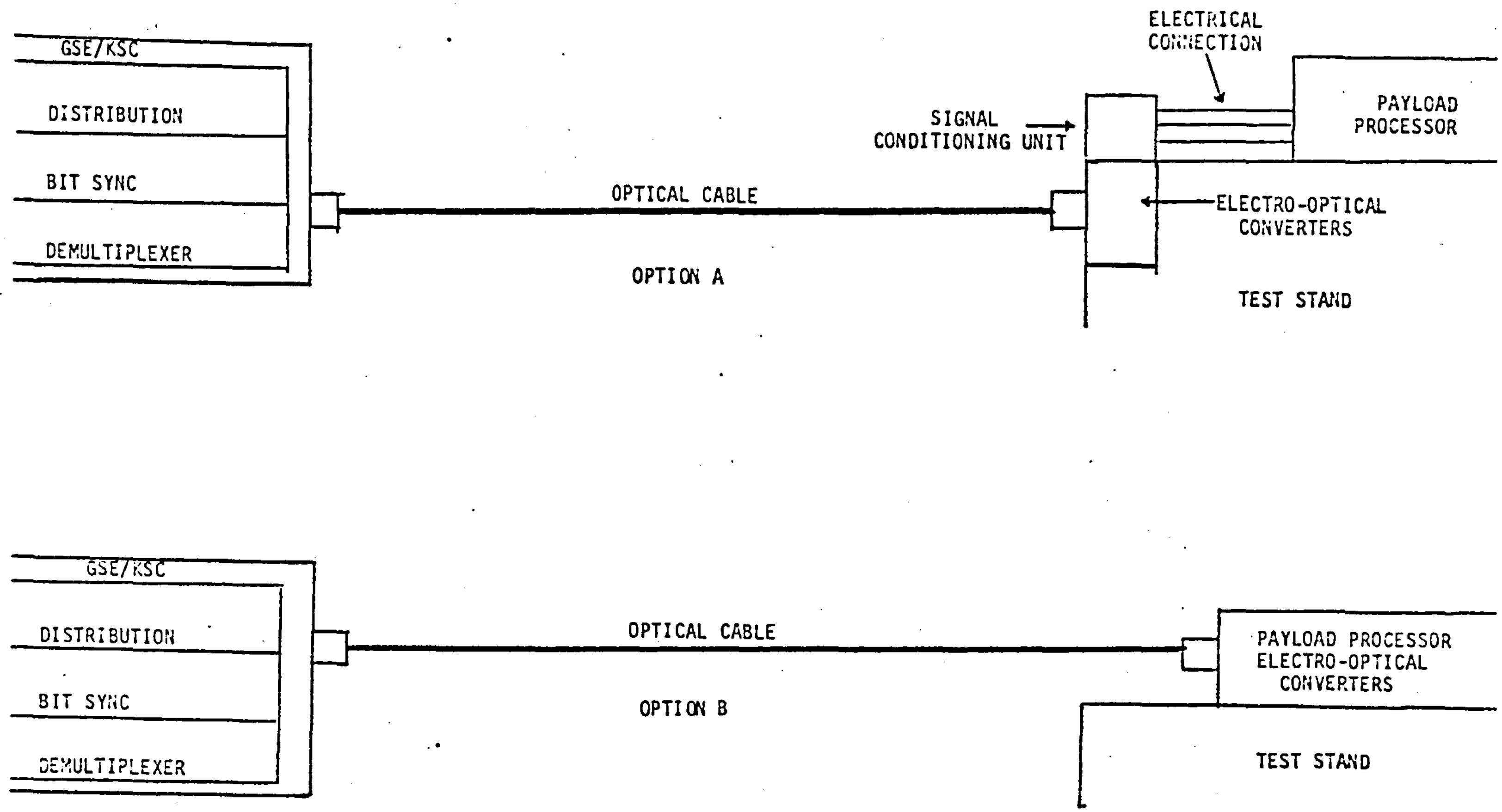


FIGURE (6) - CANDIDATE OPTIONS

cable permanently located in the O&C building, could be used by all payloads. Each optical channel would be designed to handle a maximum of 300 Mb/s, allowing ample flexibility and capability for payload communications regardless of the data rate. This method allows for a standard optical cable and dispenses with the intermediate signal conditioning electronics and connectors at the test stand.

Option C, shown in Figure 7, places the electro-optical interface within the connector. Optical component manufacturers have shown that some optical sources are small enough to insert inside an optical connector; thereby, allowing a direct connection to the payload. The payload contractor need only supply a bulkhead connector and a simple electrical mating circuit to drive the optical transmitter. This option has several limitations: one, today's optical connectors have internal optical transmitters/receivers and are available only as a single channel device; however, multi-channel devices (2 to 8) should follow by the end of 1981. Second, the cost of these specially constructed optical connectors must be compared to optical components designed separately. Third, the payload contractor may be too far along in designing and building the payload to make changes for near-term payloads. Fourth, the optical transmitter may not be capable of transmitting at a high enough data rate (discussed in Section 4.1.2). Fifth, the survivability of the optical sources within connectors after being dropped or misused is unknown. Further, maintainability of this option may require replacing cable, connector, and optical sources rather than just the damaged optical sources. Therefore, once the above conditions are satisfied, this option would be best suited for low-data rate payloads (Section 2.3.1.2).

Option D, shown in Figure 7, is a direct, line-of-sight, open-air optical link with an electro-optical interface similar to Option A. Multiplexing techniques could reduce the number of channels since the laser can be modulated in the Gbit/s range. Given the option of placing the laser on the test stand or inside the payload, most payload contractors would prefer the test stand, since the laser would be of considerable weight. Finally, a cost comparison should be made between the optical diode components and cable versus the laser system to determine if there are any cost differences.

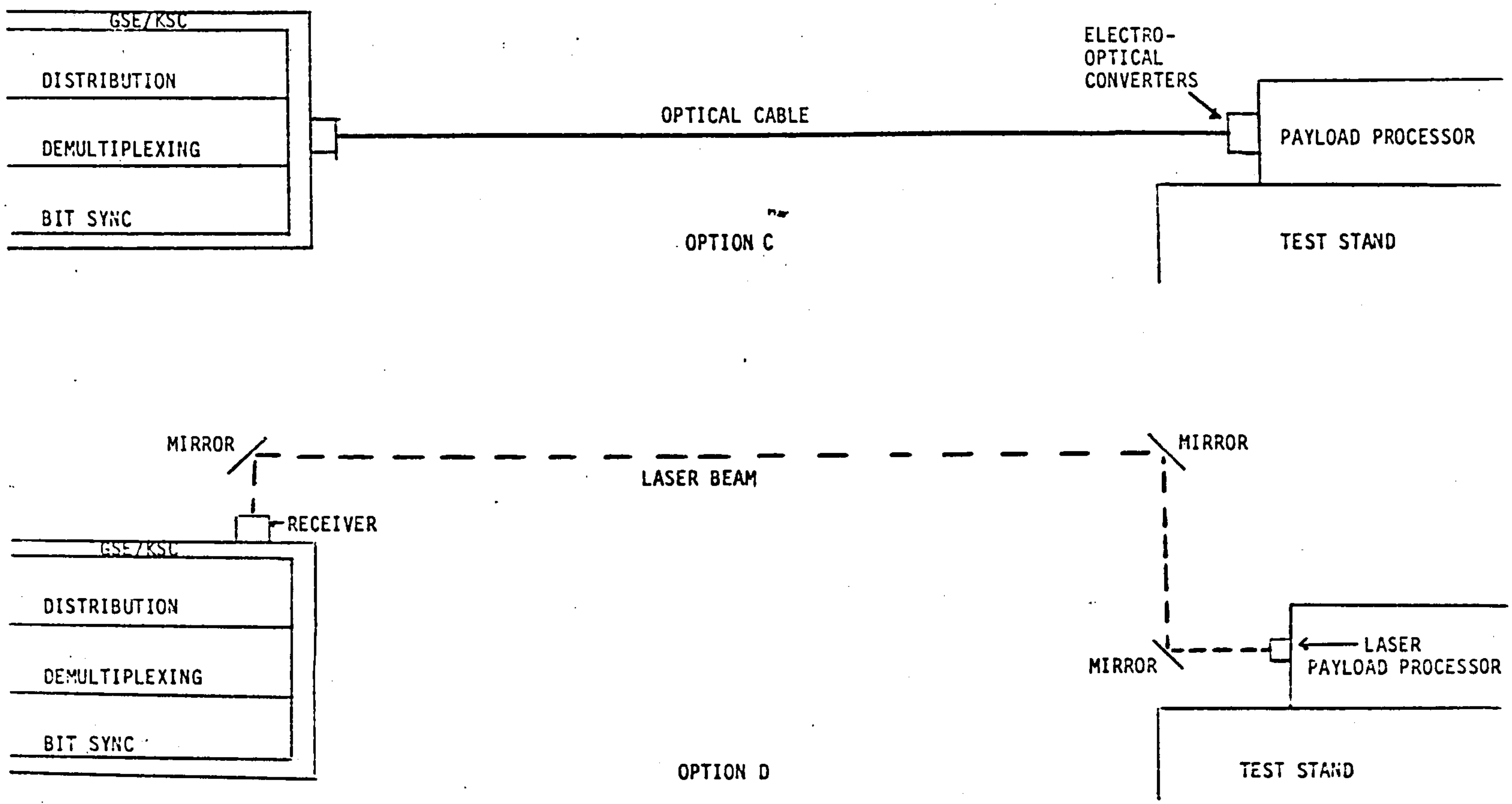


FIGURE (7) - CANDIDATE OPTIONS

In summary, Option A provides a near-term solution for transmitting telemetry from high data rate payloads - the European Spacelab is an example of this option. Option C is a near-term solution for transmitting telemetry from low data rate payloads: GRO and ERBS. Option B is a long-term solution which requires the payload contractor to supply an electro-optic interface at the payload. Option D could potentially be impractical for logistic reasons, but should not be eliminated without testing an actual system in the O&C building. Also, Option D does not take into account the likely possibility of payload contractors using optical cables to connect the payload with their GSE equipment in the PPF; thereby, making Option C the most likely candidate for the future.

3.2 OPTICAL APPROACHES FOR PAYLOAD MONITORING LINK

There are four possible fiber optic configurations for the payload monitoring link. Their differences are based on the location of the electro-optical converters and multiplexers. In addition, a laser communication system is considered as a fifth option. There will be two sets of optical-electro converters and demultiplexers, one located in the LCC and the other at the CD&SC, based on the location of the repeater in the LCC.

Option A requires a long-haul cable (20,000 feet) to connect the LCC to Pad-A. The electro-optical (E/O) converter and multiplexer would be placed in the Pad Terminal Connection Room (PTCR). A similar set of components would be used to connect the other Pad with the LCC (25,000 feet). As shown in Figure 8 all payload data passes through the T/O cables which are connected to the MLP and then brought down to the PTCR. At this point, all payload and Orbiter data would be electrically multiplexed then converted to optical signals and sent through the landlines. The advantages of Option A are reducing the number of channels now required by multiplexing a higher data rate over optical fibers and allowing for future expansion. Further, this option does not interfere with the design of the Orbiter and requires no significant change in the physical structure of the Pad. However, if any electrical cables bypass the PTCR and can be multiplexed through the optical landlines, then they must be rerouted through the Pad. If all cables bypass the PTCR, the electro-optical and multiplexers will be placed in the MLP.

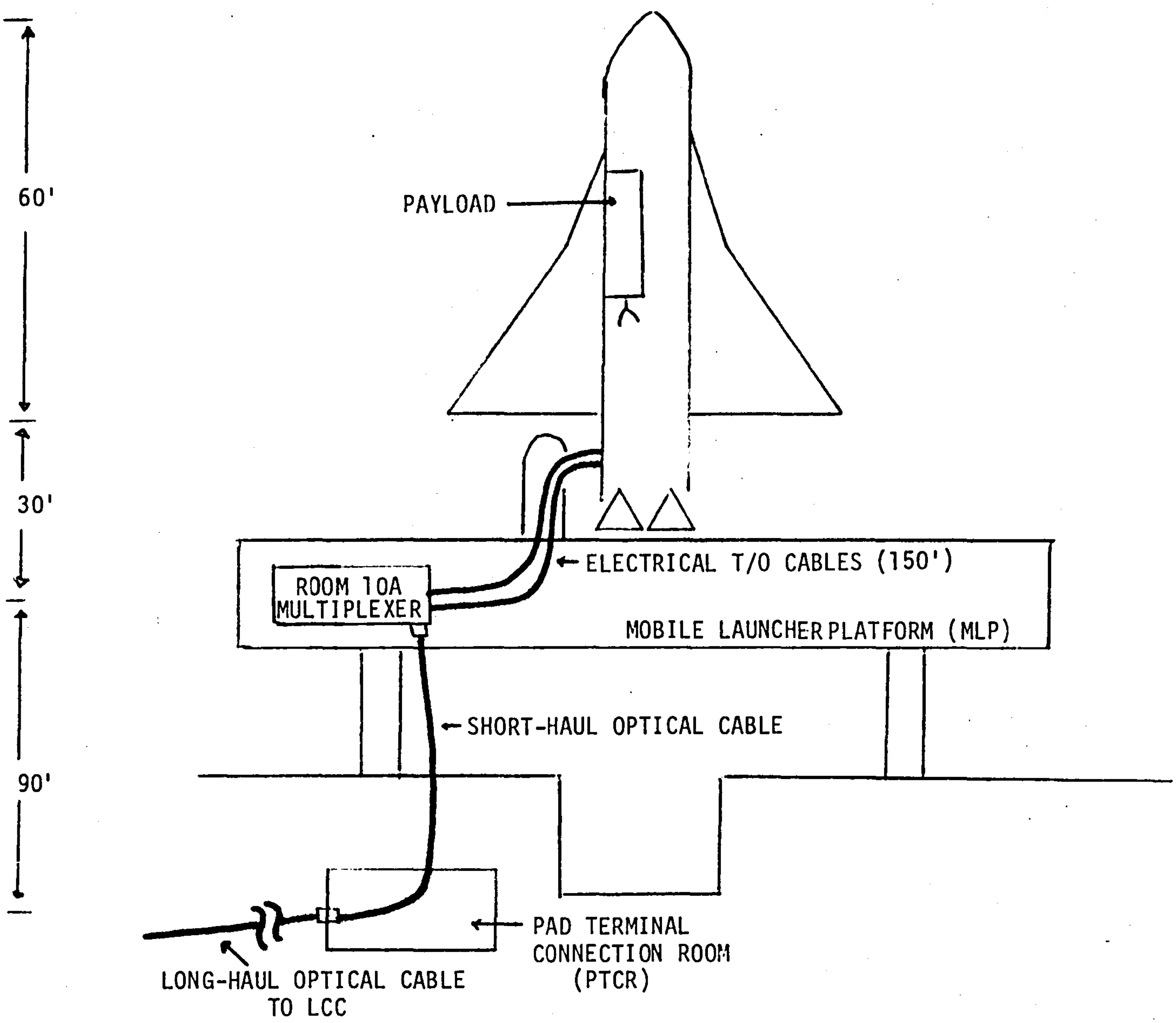


FIGURE 8 OPTION B - NEAR-TERM APPROACH FOR ORBITER/PAYLOAD LINK AT LAUNCH PAD

In Option B, as shown in Figure 8, the electro-optic converters and multiplexers are moved to Room 10A in the MLP where a direct connection with the T/O cables from the Orbiter is possible. All electrical signals going directly to the land-lines would be electrically multiplexed and converted to optical signals which would be sent through a short-haul optical cable to the Pad and connected to the landlines. Any electrical signals which do not originate from the Orbiter's T/O cables and whose destination is the LCC/CD&SC may be multiplexed and converted to optical signals. The advantages of this option are the same as Option A but also include an additional short-haul optical link. This implies fewer and lighter cables will have to be attached to the MLP. Also, this option allows for expansion of optical signals to other electrical cables that are connected to the RSS and special payload interfaces.

In Option C, the electro-optic converters would replace the present electrical interface located on either side of the Orbiter for both the left and right T/O cables. One way to accomplish this would be to convert each electrical signal to an optical signal. The T/O conversion would have to take place at or very near the wall of the Orbiter resulting in extensive vibration and shock to the optical components during launch. The effect could be to misalign source-to-fiber coupling or fiber-to-fiber coupling and possibly render the transmitters/receivers inoperative. Although flight testing of optical components has been performed with positive results, additional testing needs to be performed at the shock and vibration levels of the Orbiter. A disadvantage of this option is the signals are exchanged on a one-to-one basis requiring 120 optical interfaces. At some point before the signals are transferred to the landlines they must be optically multiplexed or the landlines would have to contain over 100 fibers. It is not possible to optically multiplex at this time, but components could be available by 1985. The other possibility would be to make an optical-to-electrical conversion at the MLP, then electrically multiplex and convert to optical signals again. Either method would prove to be more expensive, due to all the additional equipment, than the present system and offer no additional advantages or increase in the performance. A final variation would be to add an electrical multiplexer to the Orbiter at the T/O cable interface, eliminating the above problems.

In Option D, as shown in Figure 9, the electro-optic converters and multiplexers would be located within the Orbiter. The T/O cable interface would be an optical connector only, and multiplexed data from the payloads would be converted to optical signals and passed through the multiplexer. Optical components would still need to be tested but the shock and vibration levels should not be as severe as Option C. It is recommended optical connectors using lens be used at the orbiter interface due to the less critical alignment found in these connectors.

The Orbiter communication system was not originally designed to be centrally multiplexed, therefore, without any alteration to the communication system of the Orbiter, wires and fibers would have to be substituted on a one-to-one basis. Unfortunately, some communication links within the Orbiter may have longer lengths to reach the multiplexer than the original wires terminating at the T/O interface. In general, however, unshielded fibers potentially have lower weight and save space as compared to the present electrical cables.

The full potential of this option will not be realized until the Orbiter communication system is redesigned to transmit higher data rates through the optical fibers. It is recommended a data bus system using high data capacity optical fibers and a multiplexing/distribution system could substantially reduce the weight and space occupied by shielded electrical cables. This study should be followed by the substitution of an optical link for a noncritical link for test purposes. This technique has been followed by the Naval Ocean Systems Center (NOSC) and McDonnell Aircraft Company (MCAIR) St. Louis on the Airborne Light Optical Fiber Technology (ALOFT-U.S. Navy Contract No. N00123-76-C-0324) project with favorable results.

The purpose of the ALOFT project was to flight test and evaluate the effectiveness of a fiber optics interface communications system in an operational aircraft. Signal wiring in the navigation weapon delivery systems (NWDS) of a Navy A-7 aircraft was replaced by electronic multiplexing circuits and optical fiber interface components. After 150 flight-test hours, comparisons were made between the original A-7 wiring and the fiber optic system. From

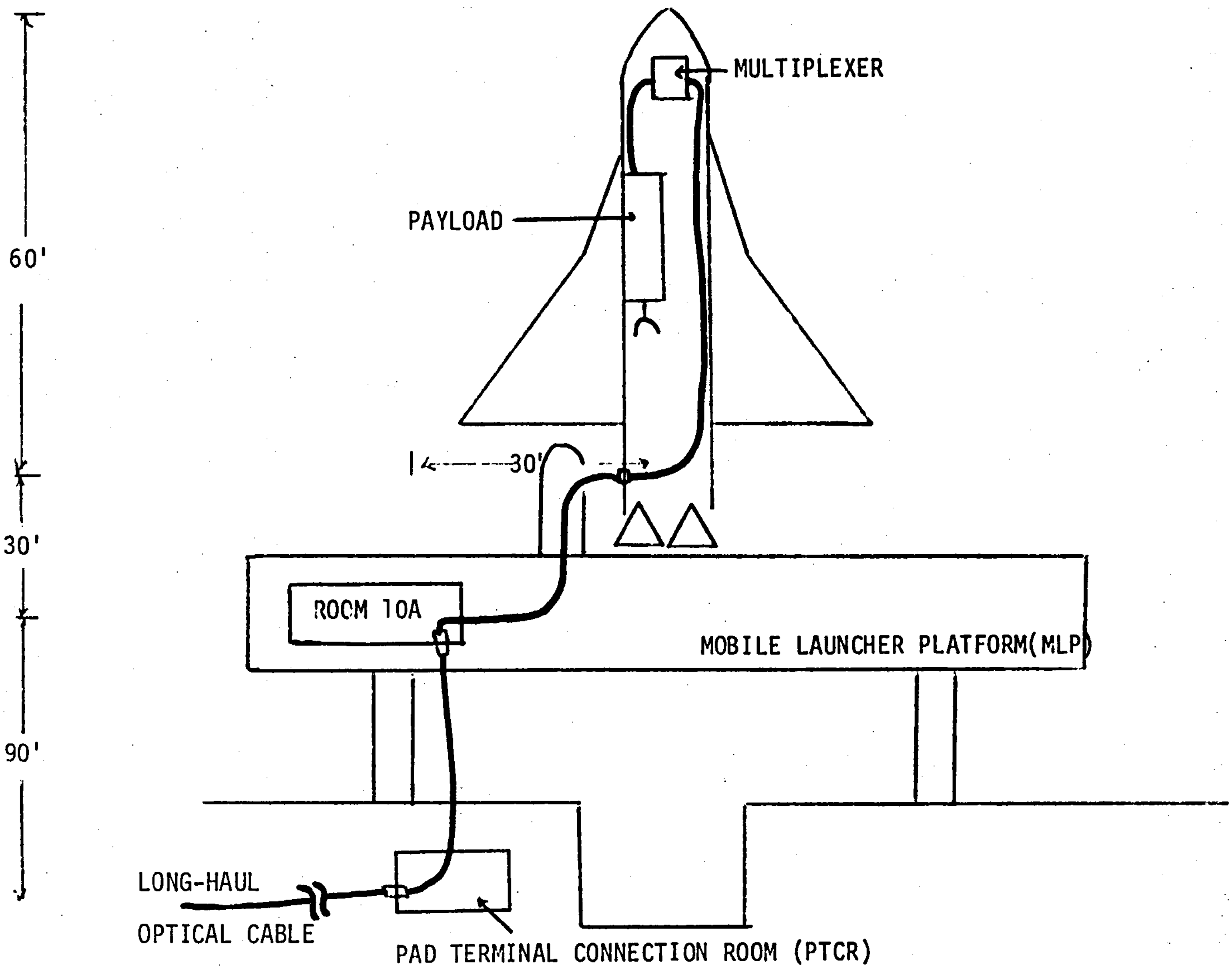


FIGURE 9 - OPTION D - LONG-TERM APPROACH FOR ORBITER/PAYLOAD LINK AT LAUNCH PAD

the final report, it can be shown: EMI immunity, weight reduction, reduction in system transient pulses produced by high magnetic induction fields, increased reliability, and total cost offsets have improved over the original copper wiring.

Option E proposes a laser and receiver to be placed on top of the Launch Pad, high enough to avoid interference with terrestial vehicles but out of the way of lightning strikes, to transmit and receive multiplexed data from the LCC. The transmission media whether it is optical fiber or wire is (1) expensive over long distances to purchase and install, (2) vulnerable to deterioration over time, and (3) may break or short-out. For those reasons, a direct line-of-sight, open-air communication system involving just a laser and receiver may look attractive.

Comparing the glass fiber to open-air transmission reveals that glass fibers inside a cable maintain a constant intrinsic transparency due to their enclosure from the environment by cabling. Air has varied degrees of transparency resulting from weather conditions (humidity, fog, rain), pollution conditions (duct, airborne particles), and life forms (insects and birds). This application requires 100 percent transmission of data, but if a narrow beam is used, a flying object could cause a shadow to fall across the receiver. Since light does not have the capability of bending around corners, the beam must be sufficiently widened to compensate for flying objects such as birds. This may be accomplished by diverging the laser beam onto a parabolic mirror, larger than any object capable of covering it, to be received by another parabolic mirror or similar size. Widening the beam has the negative effect of reducing power to the receiver, making transmission through adverse weather conditions more difficult.

There are additional problems. A redundant laser and receiver must be on standby mode in case of a malfunction so 100 percent transmission can be maintained. The laser, receiver, and mirror should be checked after each launch considering the severity of shock and vibration. Also, deterioration of the mirror surfaces from moisture, pollutants, and exhaust fumes will reduce the laser power to the receiver.

There are few working applications of a line-of-sight laser system available to refer to, nevertheless, research into such a system has been going on for years at MDAC-St. Louis. Our Laser Communications Program has been studying and designing a satellite system to communicate with other spacecraft, aircraft, ground stations, and submerged submarines. Study and analysis of these communication links indicate a high probability of success, and present testing of a ground-to-aircraft system has proved successful. It is recommended, after sufficient study, a one-way laser communication system be set up as a redundant link to the S-band transmitter on the Launch Pad. Test results will indicate the reliability of the optical components to adverse environmental effects, frequency of maintenance, and most important--the ability to communicate through a combination of birds, adverse weather conditions, and exhaust fumes.

In summary, there is very little difference between Option A and Option B. Option B adds another optical link which potentially makes connection of the MLP to the Pad quicker and easier. The location of the multiplexer in the MLP allows for better distribution of signals due to a more central location and the direct connection of the T/O cables from the orbiter.

Both Option C and Option D require coordination between the NASA agencies overseeing the Orbiter GSE/launch equipment and the Orbiter itself for complete compatibility of the proposed optical communication system. This study was only intended to cover the payload/Orbiter support communications equipment, but the advantages of converting from electrical transmission to optical transmission for the Orbiter can be easily guessed at, such as: weight and space reduction of communication cables. Further, the ALOFT program clearly demonstrated that a number of advantages exist for fighter aircraft which have some similar performance and operating conditions as the Orbiter. Option C offers no additional advantages over the first two options in terms of data handling or removal of the T/O cable during launch since this cable is attached to a plate with other cables. Modification of the Orbiter will result only in the disadvantage of added weight due to either the multiplexer or the electro-optical converters or both. It is recommended that Option D be pursued with a trade study of the present communication system as compared to a data bus system, flight testing of optical components, and testing a noncritical link.

Option E requires analysis of the power margin versus adverse environmental conditions for 100 percent success, testing of selected optical components against damage from launch and environmental deterioration, and the testing of a redundant link.

In conclusion, only Option A and Option B can be implemented at this time without risk. Option B should prove to be more cost effective over Option A and offer several added advantages. Therefore, Option B will be considered for further analysis.

3.3 SELECTION OF OPTIMUM APPROACH

In selecting the optimum approach consideration is given to methods of multiplexing, synchronizing, formatting, and modulating of communication signals. These are discussed and evaluated relative to the two communication links (payload C/O and payload monitoring).

3.3.1 Multiplexing

There are two methods of multiplexing used in optical data handling: wavelength division and time division. Wavelength division multiplexing requires sending several signals through the same optical channel at different wavelengths. For time division multiplexing, electrical signals must first be multiplexed then the higher data rate signal is converted to an optical signal containing several signals separated in time.

3.3.1.1 Optical Wavelength Division Multiplexing (OWDM)

This section describes optical multiplexing techniques, identifies the performance parameters and then compares the three most promising methods. OWDM uses different wavelengths of light, rather than different fibers, as communication channels. These wavelengths are all multiplexed and focused into a single fiber, thereby, multiplying the data rate of a single fiber by the number of wavelengths multiplexed (Figure 10).

The number of wavelengths (channels) multiplexed into a single fiber depends on several factors: actual optical mux/demux hardware, separation of the wavelengths (larger separation for multimode fibers than for single mode), allowable crosstalk between channels, coding of the information and electronic methods of separating the channels. Presently three techniques are being developed and tested to be as multiplexers, demultiplexers, or both.

1. Angularly dispersive devices have been generally used as a demultiplexer (Figure (11)). The light from the optical fiber is collimated by the input lens, passed through an angularly-dispersive element (prism or grating) and then focused by an output lens into separate photodetectors. By reversing the process, the same device could be used as a multiplexer.
2. Filtering methods have been used for both multiplexers and demultiplexers. Multilayer dielectric films have high reflectivity for one or more channels, but high transparency for other channels (Figure (12)). Filtering devices used for multiplexers do not require strict bandpass characteristics since crosstalk is not a problem at the front end; however, filtering devices used for demultiplexing must have narrow bandpass characteristics or the wavelength separation must be large. Two channel demultiplexer devices have been fabricated directly onto the fibers.
3. Semiconductor detectors have been constructed such that different wavelengths are absorbed in successive layers. The entire detector is constructed out of a single material.

A table of the advantages, disadvantages, characteristics, and performance parameters is shown in Figure (13).

There is still controversy over the best methods of implementing wavelength multiplexing and demultiplexing. As of this time, all methods are still in the research stage; presently, MDAC-St. Louis is under contract (MMIFOT-NAS9-15585) with Johnson Space Center to design and build optical mux/demux. Using present expectations, optical multiplexers will have 2 to 8 channels/fiber; the maximum data rate/channels will approach the maximum data rate of a single channel through a single fiber; and the crosstalk will be -30 dB or better.

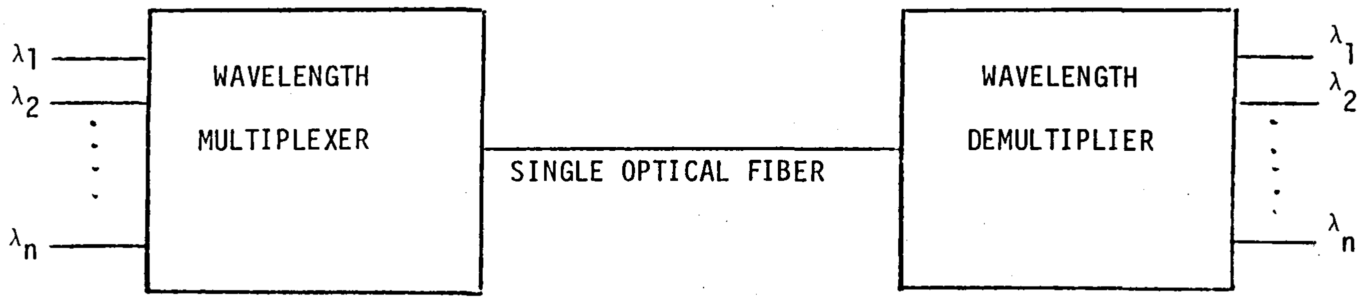


FIGURE (10) SCHEMATIC OF OWDM SYSTEM

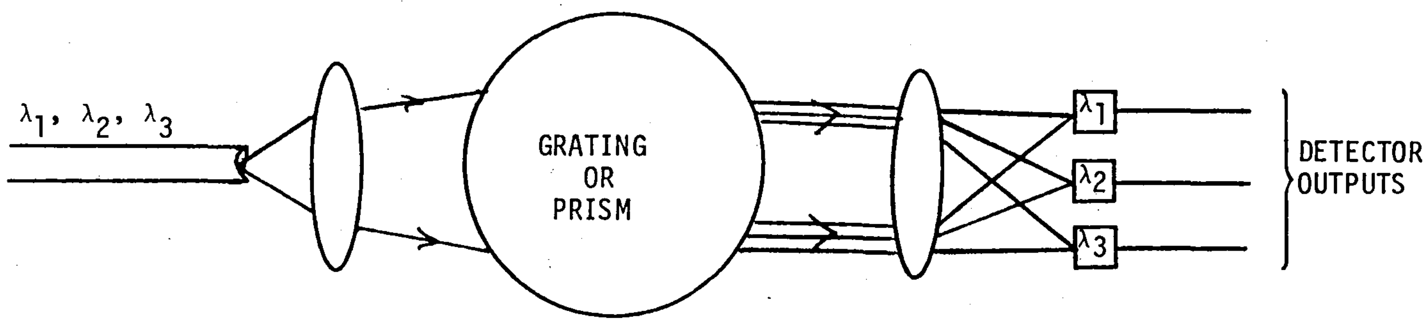
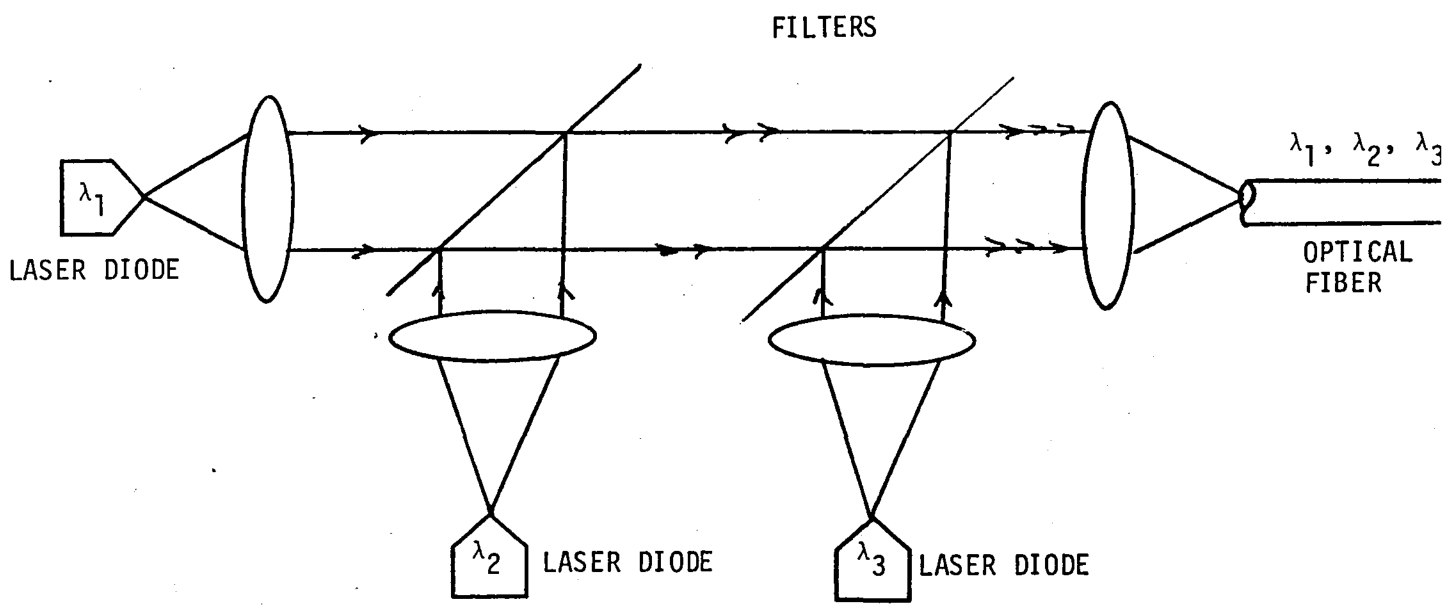


FIGURE (11) SCHEMATIC OF A DEMULTIPLEXER



FIGURE(12) SCHEMATIC OF A MULTIPLEXER

OPTICAL DEVICE	MULTIPLEXER	DEMULTIPLEXER	DESCRIPTION OF DEVICE	NUMBER OF CHANNELS	INSERTION LOSS	CROSSTALK
ANGULARLY DISPERSIVE DEVICES	MULTIMODE FIBERS MULTICHANNEL	SINGLE MODE MULTIMODE FIBERS MULTICHANNEL	PRISMS GRATINGS	2→6	1→3 dB	-20→-30 dB
FILTER DEVICES	SINGLE MODE MULTIMODE FIBERS MULTICHANNEL	SINGLE MODE MULTIMODE FIBERS DUAL-CHANNEL	MULTILAYER THIN-FILMS INTEGRATED OPTIC DEVICES	2→4	1→3 dB	-10→-20 dB
MULTILAYER DETECTORS	DUAL-CHANNEL	MULTICHANNEL	DUAL WAVELENGTH LED TRANSMITTERS SUCCESSIVE ACTIVE LAYERS OF A SINGLE MATERIAL	NOT ENOUGH INFORMATION	NOT ENOUGH INFORMATION	HIGH

FIGURE (13) TABLE OF OPTICAL MULTIPLEXING DEVICES

However, it is possible using off-the-shelf devices (optical couplers and filters) to design and construct a two channel mux/demux. This method is used on the payload monitoring link due to the long length of the optical cables, but not on the payload checkout links due to their short length.

3.3.1.2 Time Multiplexed Techniques

For the payload checkout link, time division multiplexing is performed on the payload and demultiplexed by the GSE equipment for each individual payload. Asynchronous multiplexing is required for the payload monitoring link. A discussion and comparison of the four methods of asynchronous multiplexing is based on cost of implementation and efficient use of the data capacity of the optical channels.

The techniques of handling asynchronous channels and variable data rates per channel are resynchronization of each channel, bit stuffing, oversampling, and packet telemetry. Resynchronization involves matching and adjusting the timing of several asynchronous channels to correspond with a master clock generated by the multiplexer. Resynchronization is considered the least acceptable method since a single phase-lock-loop circuit could not follow the wide, variable data rates which change frequently for most of the asynchronous channels. Several phase-lock-loop circuits covering the range of each channel would have to be manually or automatically switched. Manual switching is eliminated due to frequent data rate changes and automatic switching would require inserting a code to switch to a different circuit, presently, not available.

Bit stuffing requires determining the clock from the incoming signal, storing the data in a buffer memory and stuffing bits until a prescribed data rate is obtained. Finally, a synchronous multiplexer combines the data from each channel into a single channel. Variable data rates are handled by stuffing bits into spaces created by a slower incoming data rate to create a constant outgoing data rate. Bit stuffing is acceptable for technical reasons, since it makes efficient use of data capacity of the optical fibers. But designing the circuitry and buying components make the system expensive. The Government

Electronics Division of the Motorola Corporation has provided a description of a bit stuffing method to multiplex the asynchronous channels of the payload monitoring link:

> A system utilizing bit stuffing and resynchronization of data is shown in Figure 14. Due to the widely varying rates of this "typical" system a combination of oversampling, bit sutffing and asynchronous ("as required" rate matching) stuffing is employed. The system employs a basic rate of 1035 KHz per channel. For reduced complexity, all data inputs of rate less than 100 KHz are oversampled at a 1035 KHps data channel. This provides at least 10 samples per bit for an acceptable output data jitter for clock recovery. 128 KBps data is oversampled by a factor of 8 and asynchronously stuffed to a 1035 KBps rate. Similarly, 256 KBps data is oversampled by a factor of 4 and asynchronously stuffed to 1035 KBps. One megabit data is synchronously stuffed at a 32/31 rate to 1032 KBps and asynchronously stuffed to 1035 KBps. The 1024 KBps channels are each asynchronously stuffed to 1035 KBps. The 5 Mb/s channel is synchronously stuffed to 5.16 MBps then demuxed to five 1035 KBps channels.
>
> Five overhead channels are added to the previously described 19 data channels for a total of 24 channels of 1035 KBps data. The overhead channels are used by the receiver to detect the position of the various data channels within the stream and also to indicate the position of the asynchronous stuff bits within the data stream. In all, two synchronous stuff circuits and 8 asynchronous stuff circuits were required to multiplex the data.
>
> The receiver circuit for this approach is even more complicated than the transmitter. In all, 15 phase lock loops, 8 asynchronous destuff circuits and two asynchronous destuff circuits would be required to return the data to its original format. As a result of this complexity, this approach does not appear to be a realistic candidate for the system.

Oversampling accommodates both the problems of asynchronous channels and variable data rates by sampling at a rate much higher (8 to 10 is generally considered adequate) than twice the maximum data rate per channel. How much higher the oversampling frequency must be is determined by the amount of allowable distortion in the resulting waveforms after demultiplexing. The oversampling process attempts to reconstruct the waveform by first, a combination of rapidly sampling the original signal and then multiplexing all the asynchronous channels together, and by second, a combination of demultiplexing

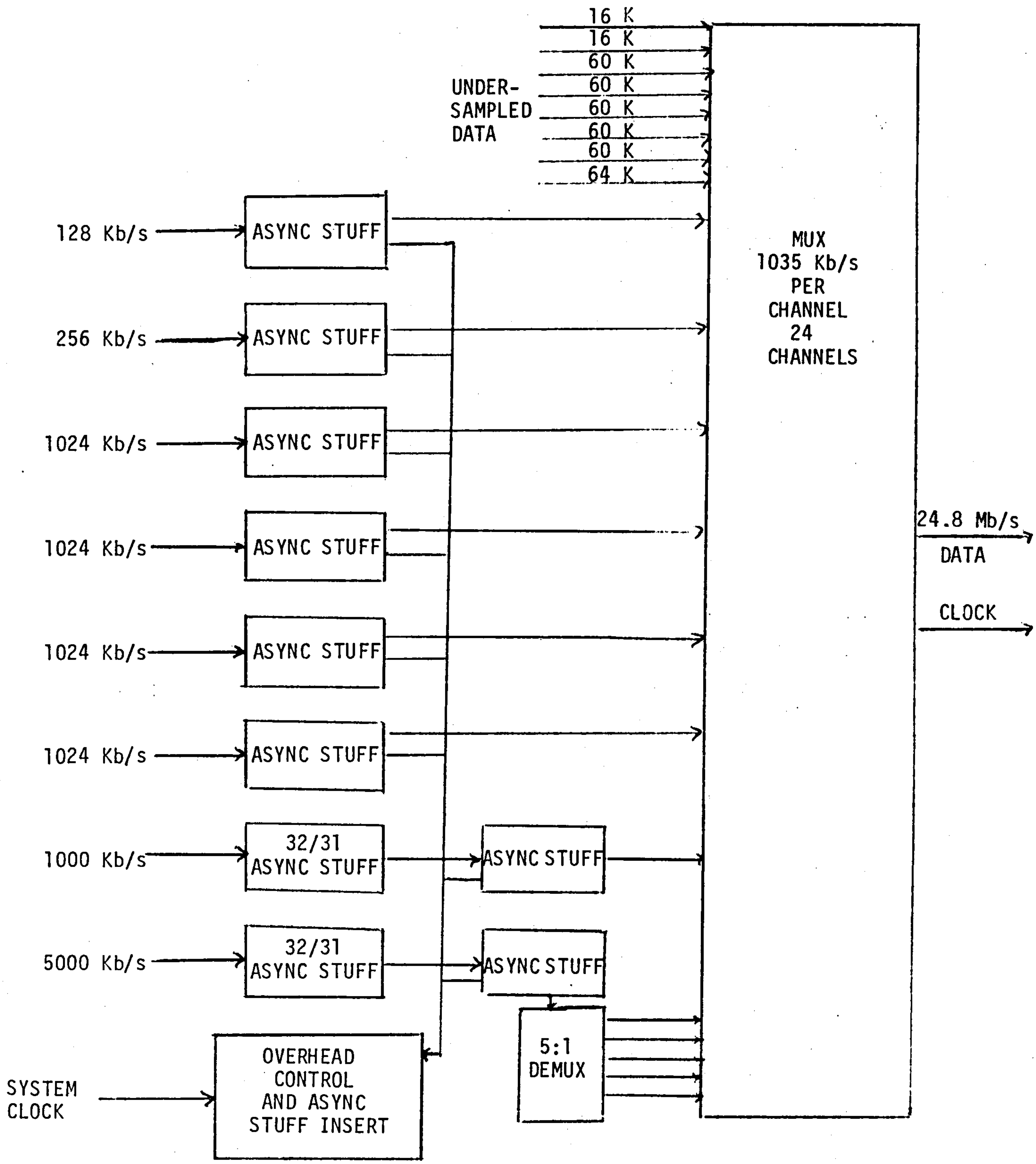
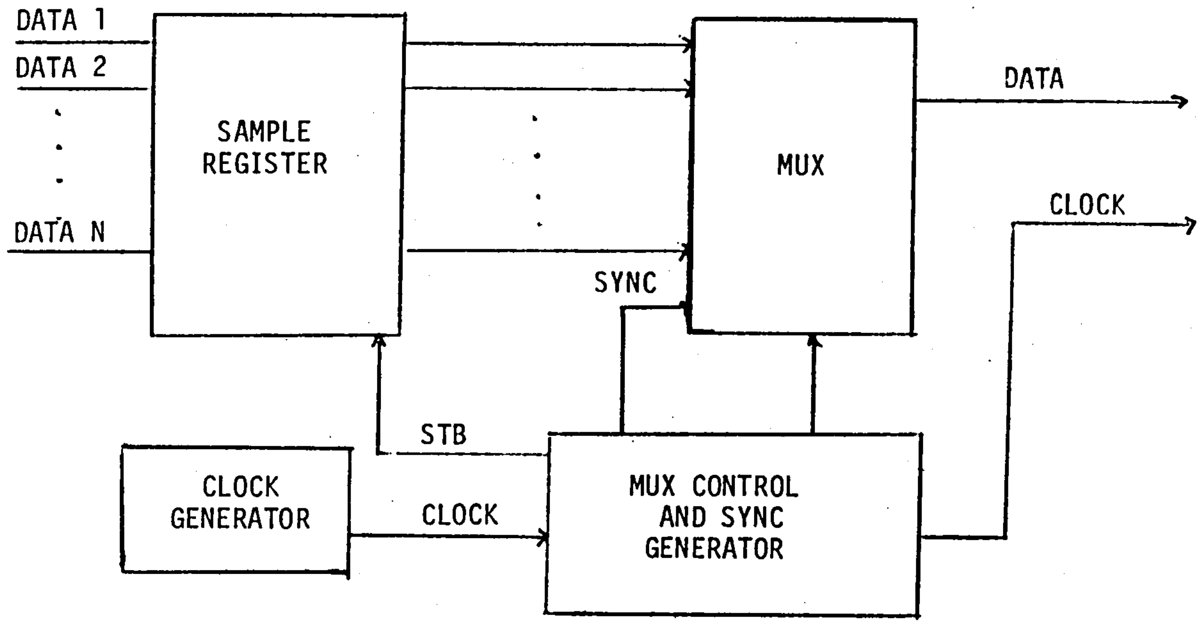


FIGURE 14 RESYNCHRONOUS AND BIT STUFF BLOCK DIAGRAM
COURTESY OF MOTOROLA CORPORATION

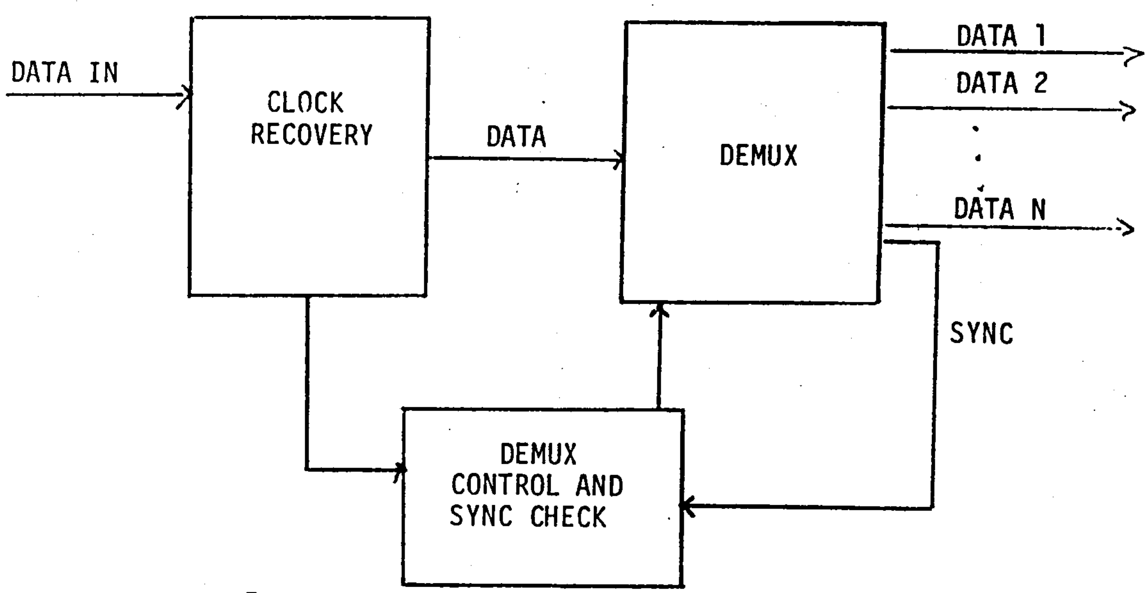
the signals by eliminating the high frequency variations by employing a smoothing circuit. Two conditions must be met for use of this method. The slightly distorted waveform resulting from the oversampling process must meet the requirements of the receiving electronic equipment; this can be accomplished by adjusting the oversampling frequency. For the other condition, the individual channel clocks must be known to the receiving electronic equipment as the data rate changes to a new discrete level. This may be accomplished by setting the individual channel clocks separately or determining the clock from prior knowledge. Again, Motorola explains the method of implementing this approach:

> The oversampling approach to the data link is by far the simplest solution. A typical system would be configured as shown in Figure 15A. A number of inputs are digitally sampled in the sampling register. These sampled inputs are multiplexed together with one sync channel to provide the output data stream. Control for the multiplexer and sampling register is provided by an oscillator and divider chain. Sampling rate for the channels is set at approximately 10 times the highest data rate channel. The output data rate is then the sampling rate times the number of channels plus one. A typical system operating at a 100 MBps output rate could accommodate 99 channels with maximum bandwidth of 100 KBps. Alternatively, if some channels were sampled more frequently than once per scan, higher bandwidths and better efficiency would be realized. An example of this option would combine 5 channels of 1 MBps data with 49 channels of 100 KBps (or less) data for the same 100 MBps output data rate.
>
> A receiver for the oversampled approach is shown in Figure 15B. A clock recovery circuit drives a demux controller which uses the sync channel to properly route the data. If a clock is required for each channel a phase lock loop is added to each channel to generate the clock. If the alternate approach mentioned for the transmitter is used to create the five 1 MBps channels, five additional multiplexers could be added to reconstruct the data or the demux circuitry could be modified to sample the data stream ten times per scan to obtain the same effect.

The packet telemetry approach accommodates the asynchronous channels and variable data rates by collecting the data in a buffer memory, packetizing the data, and finally partially or entirely filling an available time frame. If the NEEDS concept is implemented all data will be configured in packets at the origin of the data. The Motorola Corporation shows how the method could be used for the present application of the payload monitoring link:



(A)



ROM COST: $\$1\bar{M}$

(B)

FIGURE (15) BLOCK DIAGRAM OF OVERSAMPLING TRANSMITTER (A) AND OVER SAMPLING RECEIVER

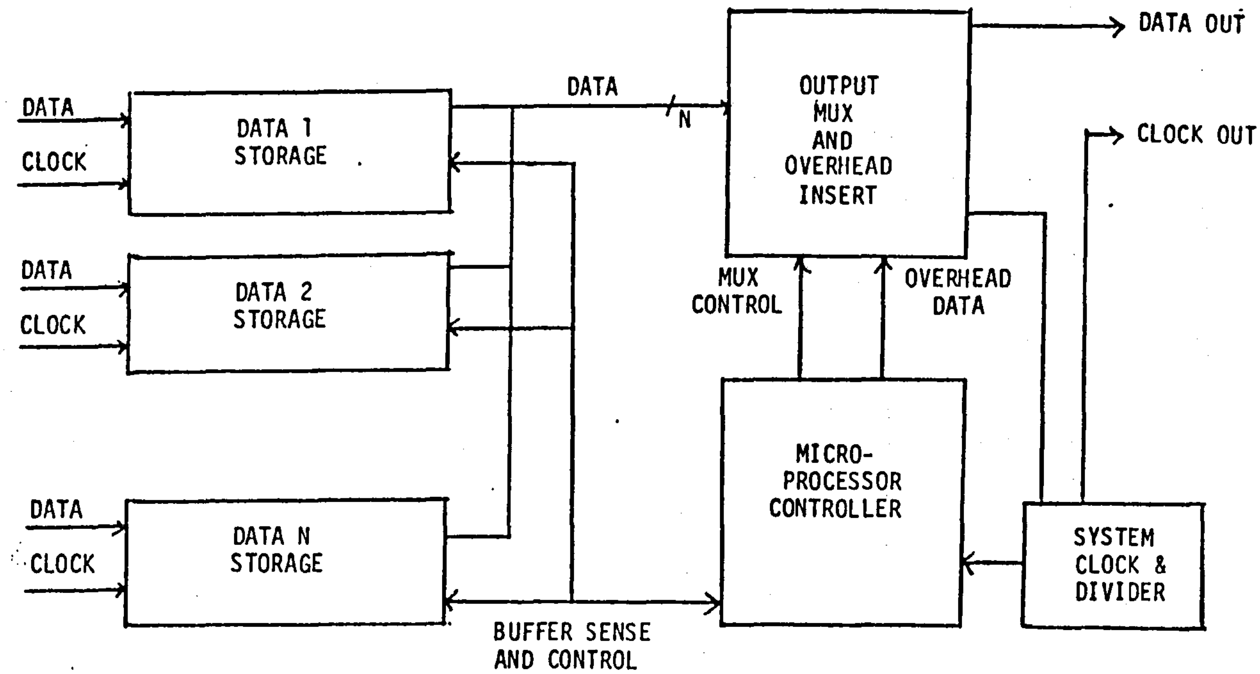
COURTESY OF MOTOROLA CORPORATION

A packet telemetry solution to the problem would provide a flexible system which could be modified by modular hardware additions/deletions and relatively minor software changes. A block diagram for a possible packet transmitter, receiver is shown in Figure 16. A number of data storage elements are controlled by a microprocessor. Each data storage element is configured as shown in Figure 17. Two memories are employed in ping-pong fashion so that no data is lost. The two memories alternately fill and empty. Each time a memory is filled, an Interrupt Request (IRQ) is sent to the processor. The requests from the various storage elements are handled on a priority basis with the highest data rate channel receiving the highest priority. As one channel's buffer becomes empty the processor enables handover to the next full buffer. To enable the receiver to correctly select the next channel at handover, a low rate overhead channel is synchronously multiplexed into the data.

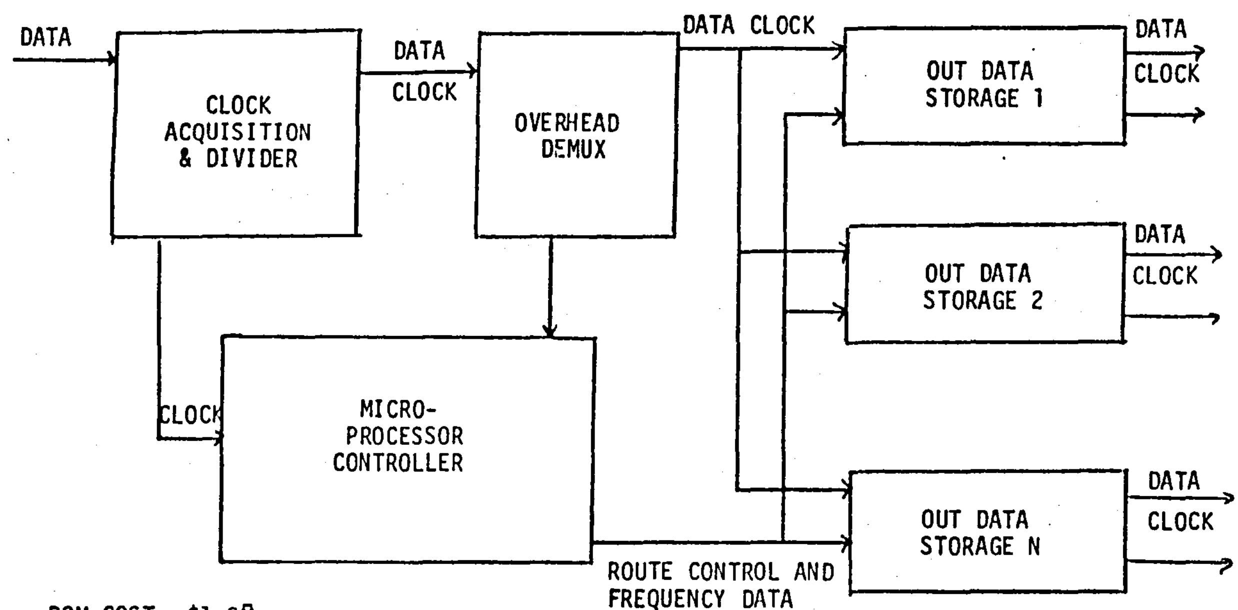
An optional circuit is included in the packet transmitter. This circuit is a frequency measuring device which provides a "fine tune" effect on the receiver frequency. As the data at the receiver is returned to its original serial format, the receiver clock is adjusted packet by packet to match the output data rate to the input. If the data is to be processed in packet format without reconversion this circuit would not be required.

The receiver section of the packet system employs a clock acquisition circuit which recovers the system clock and converts the data to NRZ format. Overhead data is stripped off and used by the microprocessor controller to enable the appropriate output data element. A typical output data element is shown in Figure 18. A ping-pong buffer is employed as in the transmitter. This buffer is enabled on the fill side by the processor element enable and a packet sync detector circuit.

Frequency data is extracted and sent to a phase lock loop output clock generator which dumps the buffer at a rate which is equal to the fill rate.



(A)



ROM COST: $1.3M

(B)

FIGURE 16 PACKET TRANSMITTERS (A) AND PACKET RECEIVER (B)

COURTESY OF MOTOROLA CORPORATION

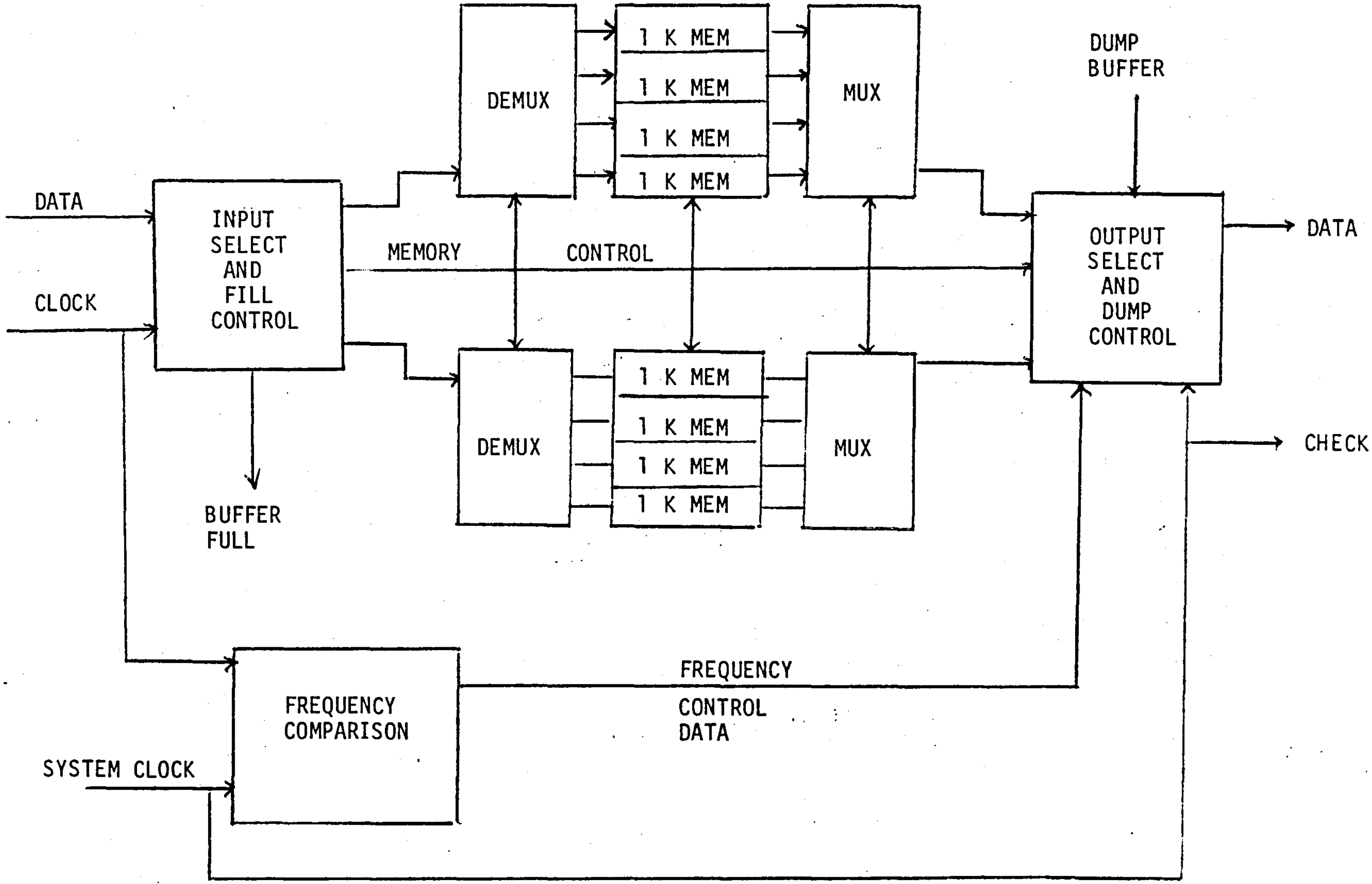


FIGURE 17 PACKET TRANSMITTER DATA STORAGE BLOCK

COURTESY OF MOTOROLA CORPORATION

This system has the advantage of having many common elements in both the transmitter and receiver. It is simple to reconfigure as overall system needs change. It is particularly advantageous if the data could be used in the packet format without reconversion back to the original format. Due to the problem of potential data overflow or underflow at the receiver end, the clock restoration operation adds considerable complexity to the circuit. Another disadvantage to this approach is the sizeable quantity of memory required for implementation. Each channel requires two packets worth of memory at both transmit and receive ends. Memory is shown as being in four segments for each buffer. This is to reduce the speed requirement on the memory. For a 100 MBps system the memory in this approach would operate at 25 MBps.

Of course, further depth demultiplexing could reduce this further. Packet size is determined primarily by the time in which the processor is allowed to access the memory handover. At 100 MBps a 4K packet similar to the NASA telemetry standard would allow 40 microseconds for computation. This seems to be about the minimum tolerable. For this size packet a 16-channel system would require 256K of memory for the transmit and receive functions.

Figure 19 compares the four multiplexing techniques based on channel efficiency and relative cost. The channel efficiency is calculated by taking the ratio of the useful, input information to the total allotted time frame. Useful, header repeated information, and empty space make up the total time frame. The relative cost is determined by comparing the complexity of design and the amount of components for each of the techniques. It may be concluded that for the 1990s both the payload checkout link and payload monitor links will be using the time multiplexed packet telemetry technique.

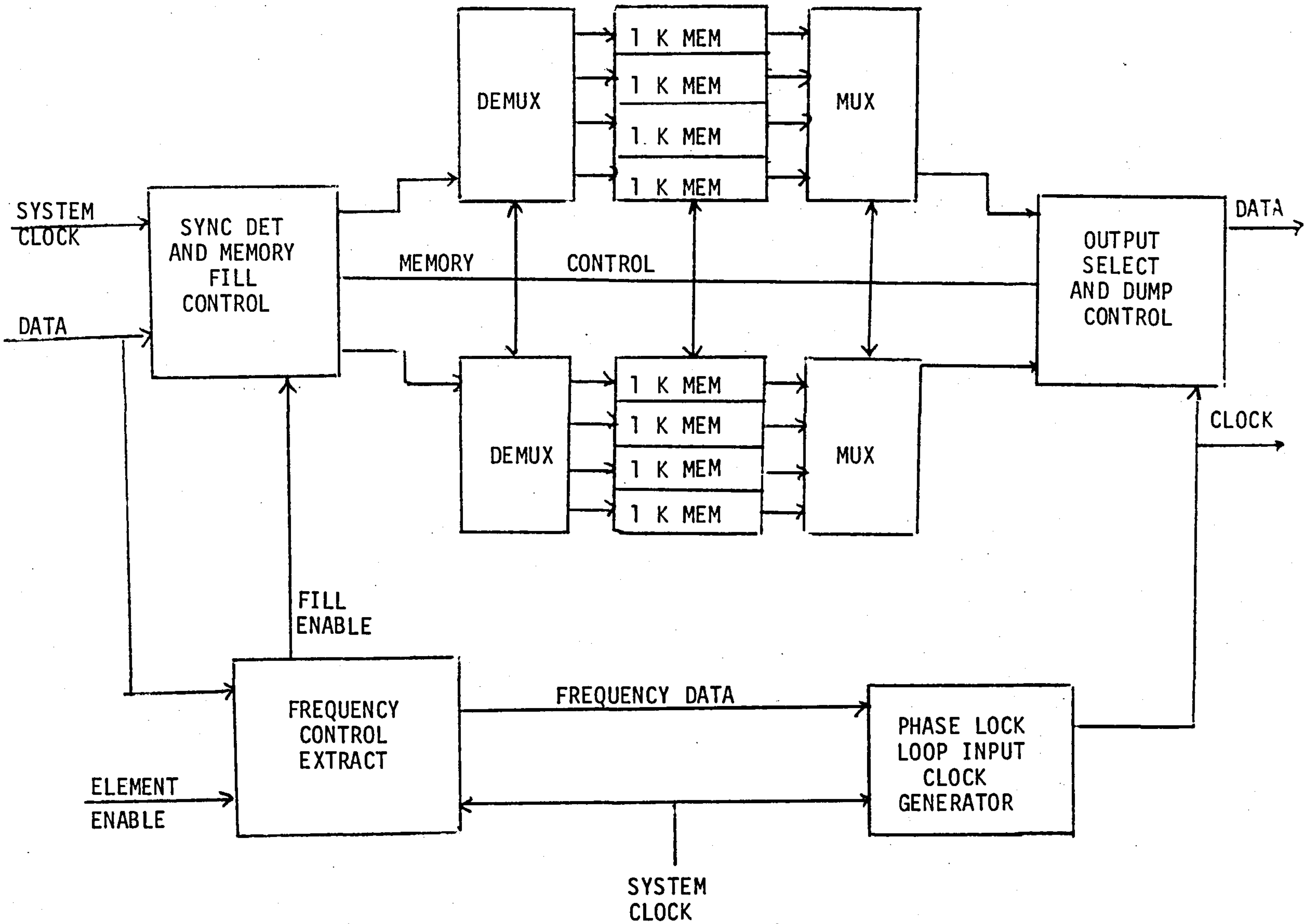


FIGURE 18 PACKET RECEIVER DATA STORAGE BLOCK DIAGRAM

COURTESY OF MOTOROLA CORPORATION

ASYNCHRONOUS MULTIPLEXING TECHNIQUE	EFFICIENCY	COST	REMARKS
RESYNCHRONIZATION	100%	MODERATE	VARIABLE DATA RATES ARE BEYOND CAPACITY OF A SINGLE RESYNCHRONIZATION CIRCUIT
BIT-STUFFING	95%	HIGH	REQUIRES HIGH COST TO DESIGN AND BUILD
OVERSAMPLING	10→20%	LOW	REQUIRES ONLY SIMPLE LOW PASS FILTER CIRCUIT AT HIGH OVERSAMPLING RATE (8-10)
PACKET TELEMETRY	80%	MODERATE	NASA PROPOSES USE OF THIS SYSTEM BY 1990'S

FIGURE 19 ASYNCHRONOUS MULTIPLEXING TECHNIQUES

3.3.2 Modulation/Demodulation of Optical Signals

Besides transmitting light, an optical transmitter must be capable of modulating an optical wave in order to convey information. There are several properties of optical waves which can be modulated: intensity, phase, frequency, polarization, or direction; an analog or digital modulation format can be then used in conjunction with intensity modulation, pulse-position modulation (PPM), or pulse-code modulation (PCM). The available options are evaluated on the basis of the characteristics of optical sources and detectors, system considerations such as power margin and dispersion analysis, and availability of modulator components.

3.3.2.1 Transmitter Modulation and Receiver Demodulation Devices

An optical source can be modulated either directly or indirectly; direct modulation applies exclusively to all semiconductor light-emitting diodes (LED) and injection laser diodes (ILD). It simply requires an electrical circuit capable of applying a varying electrical signal to the input of an optical source with linear input/output characteristics at the desired modulation rate. For example, the output light intensity of a typical AlGaAs LED is proportional to the input current over a wide range of the drive current, which is important if the modulation format is analog. The bandwidth of the modulated signal can reach as high as 100 MHz, but 50 MHz is considered a practical maximum. For modulation rates approaching 50 MHz, a small DC bias current is necessary to keep the effects of the function capacitance small. Since heating effects limit the high peak current, the DC bias reduces the ratio between the on-state and off-state, thereby, reducing the system performance in terms of lower receiver sensitivity. For a ratio of 10 or more, the loss of sensitivity is 2 dB for an avalanche photodetector and less than 1 dB for a PIN diode. ILD can be directly modulated in either the analog or digital format, although second and third harmonics may pose a problem for analog modulation for some commercial ILDs. In either case, the ILD must be operated above the threshold level for linear operation. The modulation rate can reach

as high as a few gigahertz due to the stimulated emission significantly reducing the carrier lifetime ($\sim 10^{-8}$ sec). In conclusion, direct modulation has been used in nearly all applications of optical communications due to its compatibility with optical semiconductors. Also its less expensive than other methods due to simplicity and use of common electronic components.

Indirect modulation involves placing a bulk or thin-film waveguide--made out of materials whose refractive index change with applied electric fields, magnetic fields, or acoustical waves--in the path of the optical beam. These devices are not only used to change the intensity, but also the phase, frequency, polarization, or direction. External modulators are being evaluated on the basis of bandwidth, modulating power, transparency, coupling efficiency, dispersion properties, and temperature sensitivity. All external modulators make use of microscopic physical effects in the transparent medium to make small changes in the refractive index. Modulation can be accomplished by changing the applied electric field, changing the applied magnetic field, or applying an acoustical wave. Electro-optical modulators, using a linear electro-optical (Pockels) effect (Figure 20), show the most promise, because all forms of modulation are possible, wide-band operation can be achieved, modulation is possible at all optical wavelengths, electro-optic modulators have good coupling properties, and are not expensive or difficult to fabricate as compared to other modulator types. For example, in the MDAC-St. Louis Laser Communications Program a $LiTaO_3$ crystal has been thoroughly tested and is designed to operate at 1 Gb/s. Bulk acousto-optical modulators (Figure 21) use any transparent medium in which an acoustical wave causes periodic refractive index changes due to a photoelastic effect; these devices are usually limited to 200 MHz bandwidth--transit time of the ultrasonic wave across the carrier beam. Amplitude modulation of the ultrasonic wave results in a corresponding intensity modulation of the diffracted beams. Frequency modulation of the acoustical wave causes frequency modulation of the diffracted beams. Acousto-optic modulators are useful in laser frequency shifting for tuning a local oscillator in heterodyne detection. Bulk magneto-optical devices usually have limited optical transparency. All these devices can be used with monochromatic, single mode, single-polarization sources. In conclusion while

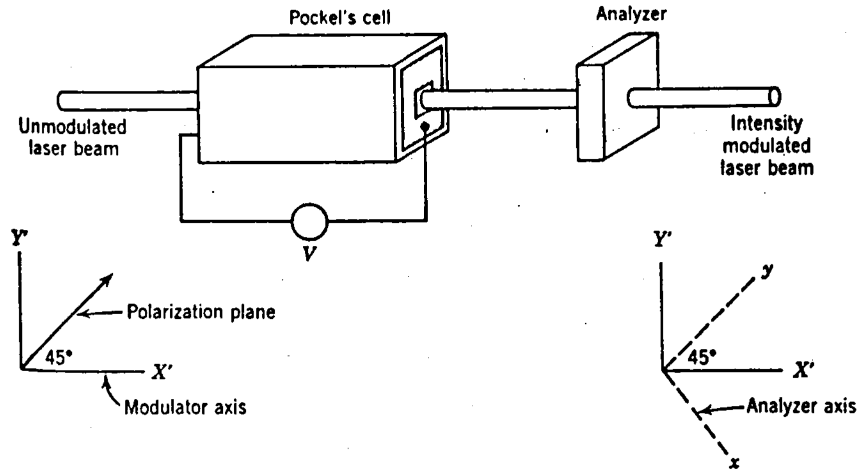


FIGURE 20 ELECTRO-OPTICAL INTENSITY MODULATOR

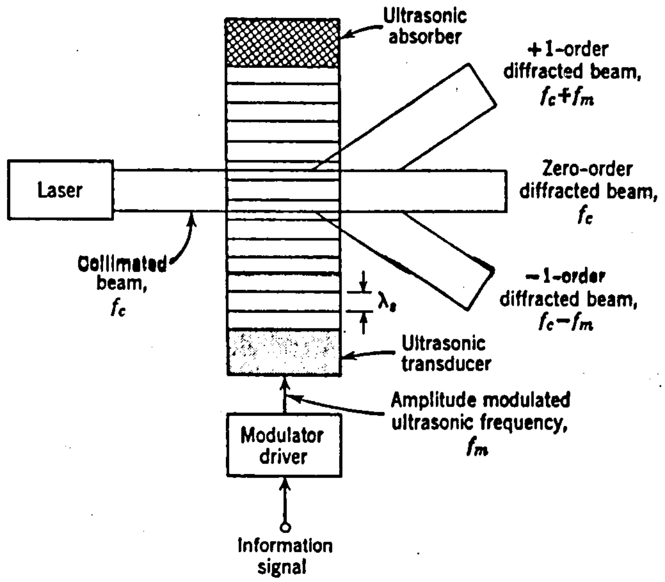


FIGURE 21 ACOUSTO-OPTIC MODULATOR

indirect modulation is feasible and has numerous advantages, bulk and waveguide modulators are still in the research stage.

Generally, all optical receivers designed for the near future use direct detection (photon counting) of intensity modulated optical waves. Heterodyne detection, while commonly used in radio wave detection, is only used to demodulate phase and frequency modulated optical waves. This limited use results from the severe requirements of a stable, single frequency, single mode optical sources to produce the carrier wave and a local oscillator.

In conclusion, for the present applications and the 1980-1985 time frame, optical transmitter and receiver diodes should use direct modulation/demodulation of intensity formatted data. Other methods such as phase, frequency, or polarization, using external modulators and lasers, presently show no apparent advantages for this application and are still under research. Beyond 1985, future systems may use combinations of modulation techniques to transmit several channels through a single waveguide and avoid crosstalk problems.

3.3.2.2 Modulation Format

Due to the selection of a direct method of signal modulation, three methods of formatting the signals are evaluated: intensity modulation, pulse position modulation, and pulse code modulation. The payload checkout link is expected to transmit only digital data. The payload monitoring link transmits a majority of analog signals.

Three common modulation formats are used to transmit analog information. First, intensity modulation simply reflects changes in the input analog signal by varying the optical signal from zero to a peak value and then reconverting to an electrical signal at the other end. Second, for pulse position modulation (PPM), the baseband analog signal is sampled at twice the frequency of the incoming signal. Encoding is accomplished by positioning these samples (narrow pulses) within a time frame according to the intensity of the input signal. At the receiver end, the PPM detector measures the time displacement and recreates the intensity of the voltage, a filter then reconstructs the analog

signal. At the receiver end, the PPM detector measures the time displacement and recreates the intensity of the voltage, a filter then reconstructs the analog signal. Third, pulse code modulation (PCM) also samples the analog signal, but assigns a binary code to the samples according to their intensity. The number of bits used to determine the level at intensity alters the fidelity or quality of the reconstructed analog signal: 4 to 6 bits provides adequate signal quality while 6 to 8 bits produce excellent signal quality.

In order to select a method of modulation, two graphs (Figures 22 and 23) provide a way of comparing the bandwidth against the allowable dispersion and power margin. Intensity modulation cannot be used in the payload monitoring link since low bandwidth analog signals must be time multiplexed. PPM modulation is limited in bandwidth; therefore, PCM is the best choice. For the payload checkout link, it is anticipated that for all future satellites even imaging satellites such as NOSS, PCM digital data will be transmitted. This results from digital data channels using error correcting codes producing greater signal integrity and wider bandwidth than comparable analog signals.

3.3.3 Data Format

The highest data rate which can be multiplexed into an optical fiber depends on the data format--NRZ (nonreturn to zero) and RZ (Manchester coding)--and the risetime of the optical components.

Two simple formulas relate the total risetime (dispersion) to the maximum allowable data rate for NRZ or RZ data:

$$\text{NRZ Data Rate} = \frac{.70}{\text{Risetime of Components}}$$

$$\text{RZ Data Rate} = \frac{.35}{\text{Risetime of Components}}$$

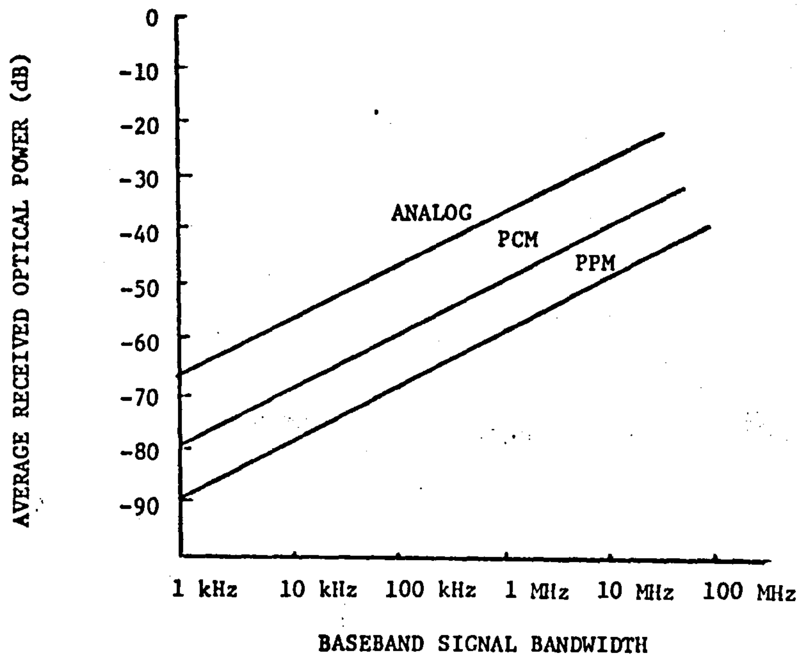


FIGURE 22 FOR SNR = 60 dB A COMPARISON OF MODULATION FORMATS BASED ON RECEIVER SENSITIVITY

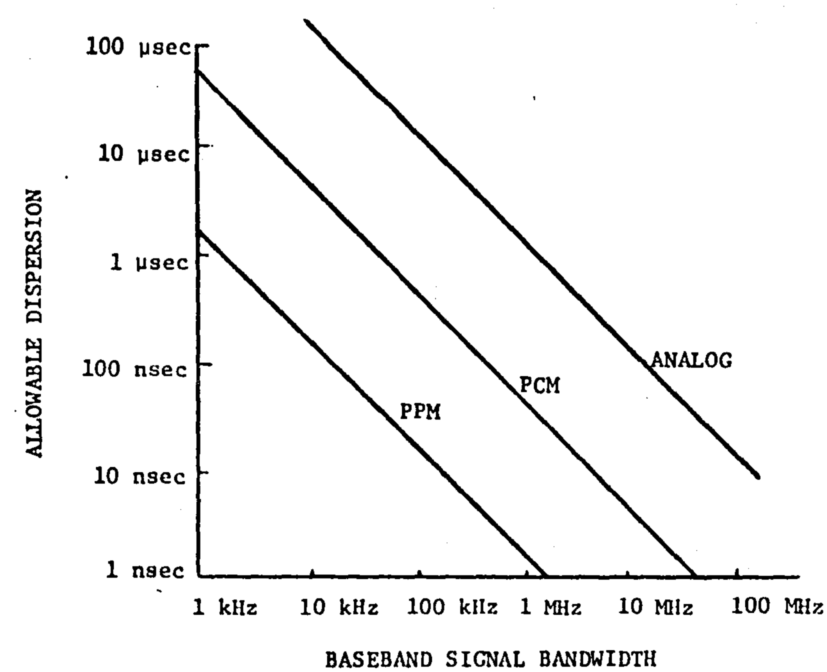
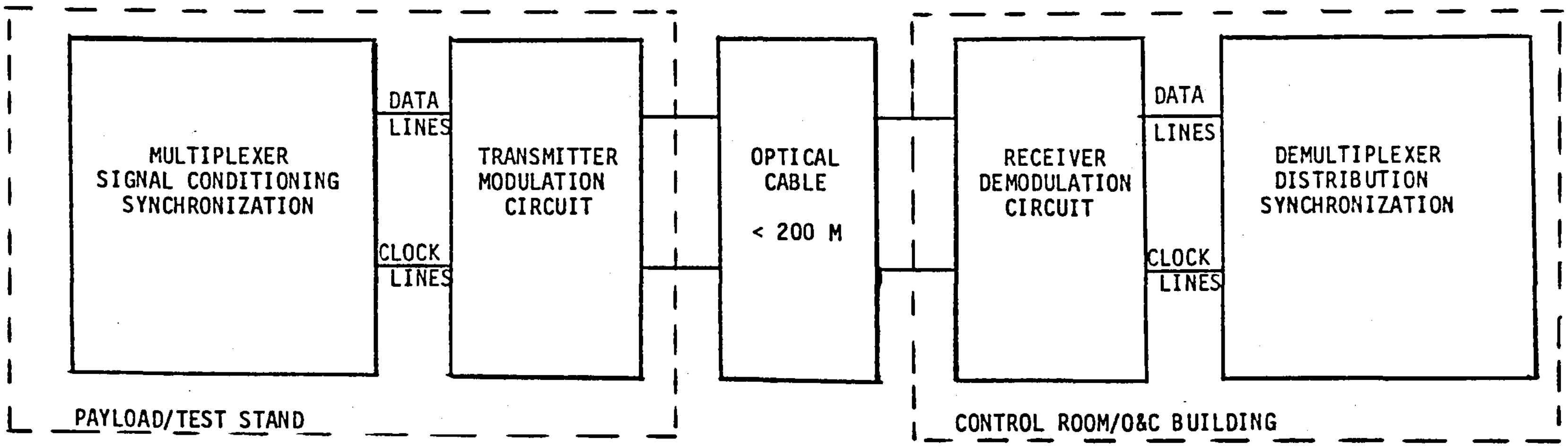


FIGURE 23 FOR SNR = 60 dB A COMPARISON OF MODULATION FORMATS BASED ON ALLOWABLE DISPERSION

Using the same risetime for each formula reveals a two-to-one relationship between NRZ and RZ coded data. This would apparently favor using a NRZ data format, except that the receiver. unlike a RZ data format, cannot extract the clock from the data stream. Therefore, the clock must be sent on a separate fiber or be duplexed with the data through the same fiber. For reasons which become clearer in later sections it is more cost effective to provide a separate fiber for the short payload checkout links and duplexing the channels into a single fiber for the long payload monitoring links.

3.3.4 Block Diagram of the Optimum Approach for Two Payload Links

In Task D, the conventional approach is compared against two optical approaches for each of the payload communication links. For the purpose of a comparison, the design of the optical approach should be as complete as possible. Therefore, the selection of the two optical approaches is based on using off-the-shelf components and well understood communication techniques. A future optical approach is included in the comparison to take into account future development of optical techniques and components. For the payload checkout link (Figure 24), Option A is the selected approach; options B, C, and D hold future promise as payload contractors are able to incorporate an optical interface into their designs, as new optical components are developed (multi-channel connectors with optical transmitters) and the logistics of using a laser system within the O&C are better understood. For the payload monitoring link (Figure 25), Option B is selected since this option does not require alteration of the Orbiter, which is not possible at this time. Options C & D, optically interconnecting the ground support equipment with the payload/Orbiter, requires further study to determine what advantages might be realized when an optical communication link is used on the Orbiter. Option E does not seem practical and may require testing. The two options for the payload checkout link and the payload monitoring link are evaluated in the next section.



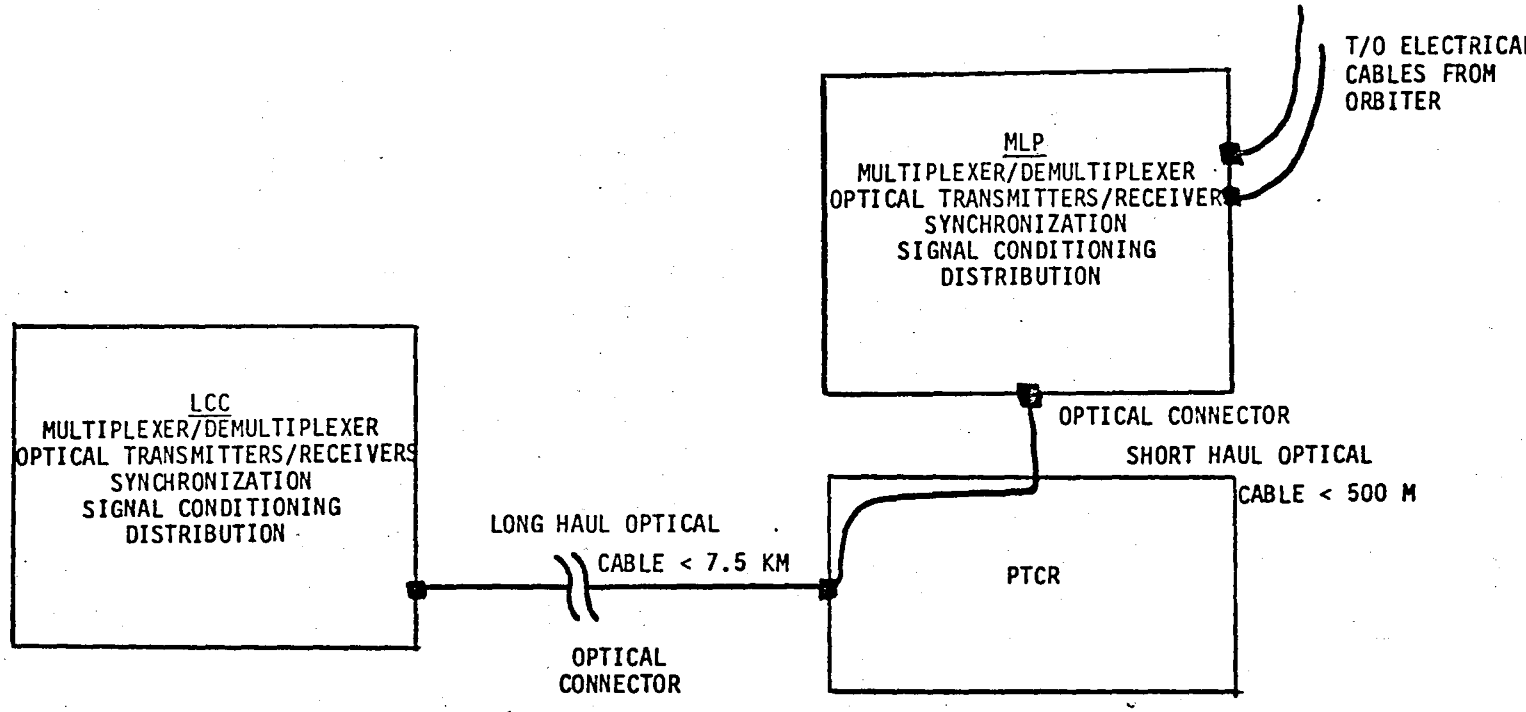
FEATURES: TIME DIVISION MULTIPLEXING

NRZ OR MANCHESTER DATA

DIRECT MODULATION

DIGITAL PCM

FIGURE 24 BLOCK DIAGRAM FOR OPTIMUM PAYLOAD CHECKOUT LINK



FEATURES: TIME DIVISION MULTIPLEXING

ASYNCHRONOUS - OVERSAMPLE

NRZ CODING

DIGITAL - PCM FORMAT

FIGURE 25 BLOCK DIAGRAM FOR OPTIMUM PAYLOAD MONITORING LINK

4.0 TASK C - SURVEY AND SELECT OPTICAL COMPONENTS

This section is divided into four parts. The first part surveys optical fibers, transmitters, and photo detectors most frequently used in fiber optic communications. Component types under each section are compared in terms of their characteristics and properties. Variations in component types are discussed briefly, but a complete explanation and comparison of all the variations of laser diodes, light-emitting diodes, P-I-Ns, and avalanche photo diodes would be beyond the scope of this report. The second part selects optical components for both communication links based on requirements stated in Section 2.3, dispersion analysis, and power margin analysis, followed by tables summarizing the parameters for each of the optical components. The third part selects electrical circuits to drive the optical components, encode the data (NRZ or Manchester), and transmit high data rate payload channels through low data rate land lines. Finally, the fourth section uses the payload monitoring link to illustrate the significant reduction in the present number of electrical channels by using optical data handling methods.

4.1 OPTICAL COMPONENTS

The concepts of signal dispersion and attenuation which play an important part of system design (Section 4.2) are developed and defined in the section on optical fibers. These two concepts are then related to the risetime and coupling loss of optical sources and detectors.

4.1.1 Optical Fibers

To introduce the concept of propagating modes, optical waveguides are first related to metallic waveguides. This leads into a discussion of the dispersion properties of step-index, graded index, and single-mode fibers. Finally the causes of attenuation in optical fibers is discussed.

4.1.1.1 Optical Waveguides

The study of optical waveguides is very similar to the study of microwave or metallic waveguides. To analyze a waveguide's capabilities, Maxwell's equation must be solved with the appropriate boundary conditions to determine energy propagation within the waveguide and continuity equations must be

applied at the interfaces to determine energy exchange. The resulting expressions provide valuable insight into signal characteristics such as: signal loss, signal distortion, and signal crosstalk; also the equations can be used to calculate the launching efficiency of the transmitter and the resulting coupling loss between the transmitter/fiber interface. The results are given in latter sections for those topics. For now, it is enough to say cylindrical waveguides have two sets of solutions to Maxwell's equations: transverse electric (TE) and transverse magnetic (TM) modes, as do closed metallic waveguides. In a dielectric optical waveguide there are additional hybrid modes which are the HE and EH. When an optical waveguide is in multi-mode operation all variations of the transverse and hybrid modes up to the cutoff frequency (the frequency below which the mode fails to exist) may be present; in single mode operation all modes may be eliminated except for the HE_{11} mode which exhibits no cutoff. The number of modes propagating in an optical fiber determines, in some cases to large extent, the amount of dispersion an optical signal undergoes as it passes through the fiber. The following sections discuss the four characteristics of optical waveguides which influence signal dispersion and signal loss: the geometry of the waveguide structure, modal characteristics of the waveguide structure, materials used in constructing the waveguides and manufacturing tolerances.

4.1.1.2 Dispersion

Dispersion limits the data capacity of a pulse-modulated communication system by producing bit smearing which is caused by intersymbol interference, and in analog-modulated transmission by producing delay distortion. Dispersion or pulse broadening is caused by numerous modes, with different phase and group velocities, arriving at various times at the detector, and by the influence of waveguide structure and fiber materials altering the velocities of different component wavelengths. Modal, waveguide, and material dispersion are present in multi-mode optical waveguides with modal dispersion dominating; however, waveguide and material dispersion are alone present in optical waveguides especially constructed for mono-mode propagation. Optical cylindrical waveguides, commercially available are designed to be either multi-mode (step or graded index) or single-mode (step index) fibers. Each type of optical fiber has different dispersion properties.

But before continuing with the discussion of dispersion, several optical parameters need to be defined, as well as their relationship with the three principal types of optical fibers. The refractive index is the optical parameter which determines if the light is guided or not. Figure 26 shows a typical optical fiber consisting of a central portion, known as the core (n_1), made of glass or plastic through which most of the energy and useful information passes through. The core is surrounded by a cladding material (glass or plastic), whose refractive index (n_2) is less than the refractive index of the core. Energy propagating in the cladding quickly goes to zero in the perpendicular direction and decays exponentially in the direction of propagation. The outer layer is protective in nature, composed usually of plastic, and is optional; its refractive index (n_3) is usually higher than the cladding for protection against crosstalk and security requirements. For the step-index fibers, the purpose of the small refractive index between the core and the cladding is to continuously reflect the light rays in a zig-zag pattern according to the laws of internal reflection within the core; for graded-index fibers, the light is continuously bent in a sinusoidal fashion.

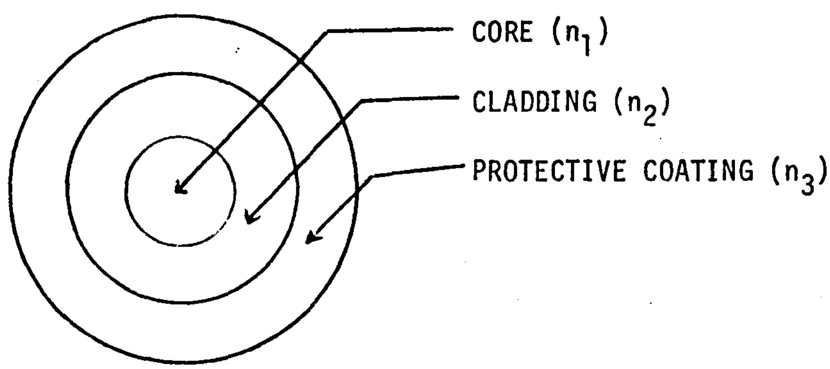


FIGURE 26
TYPICAL OPTICAL FIBER

An equation derived from Snell's law realtes the critical angle (acceptance cone half-angle) for internal reflection (θ_c) and the numerical aperture (NA) to the refractive indices of the core and the cladding:

$$NA = \sin\theta_c = [n_1^2 - n_2^2] \qquad (1)$$

Rays entering the optical fiber at an angle greater than the critical angle are totally reflected at the cladding/core interface; rays entering the optical fiber at an angle less than the critical angle are absorbed into the cladding (Figure 27). Returning to the core and cladding, the smaller the difference in the two refractive indexes, the smaller the critical angle which limits the light gathering capability of the fiber. As the critical angle is decreased, the zig-zag pattern approaches rays of light parallel to the optical axis; hence, the difference in path length, the cause of modal dispersion, between light rays bouncing off the cladding and the light rays parallel to the optical axis is reduced. Balancing the conflicting parameters of light gathering and modal dispersion is a fundamental design consideration affecting both the signal distortion and signal loss.

Another equation, again derived from Maxwell's equations, involves a parameter called the normalized frequency:

$$\upsilon = \frac{\pi d}{\lambda} \sqrt{n_1^2 - n_2^2} = \frac{\pi d}{\lambda} NA \qquad (2)$$

This equation relates the normalized frequency to the wavelength (λ), the diameter of the fiber (d), and numerical aperture (NA). Furthermore, the number of modes an optical fiber can carry is: $N = \upsilon^2/2$. The normalized frequency equation suggests three ways to reduce pulse spreading: (1) decrease

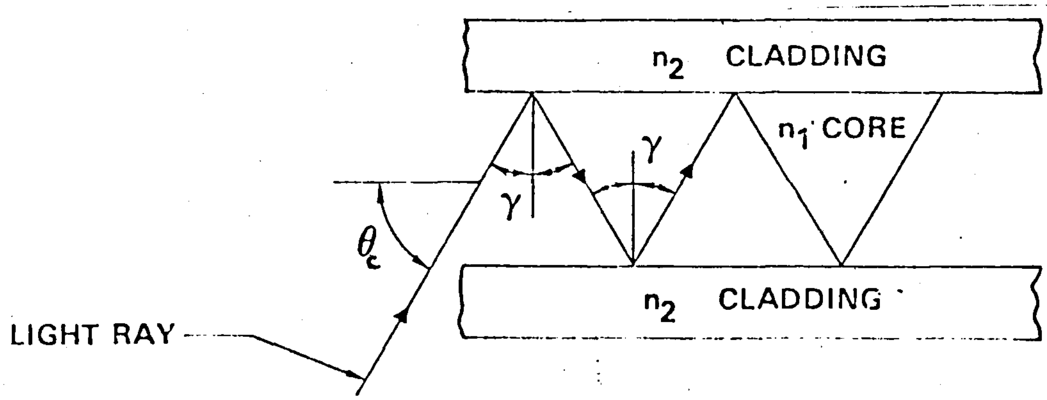


FIGURE 27
THE PATH OF A LIGHT RAY IN A STEP INDEX FIBER

the core diameter, (2) decrease the difference between the core and the cladding indices, and (3) increase the wavelength. Decreasing the core diameter and changing the difference in refractive indices are the usual methods of reducing the number of modes, and thus reducing the pulse-spreading due to different path lengths (Figure 28). The choice of wavelength is usually affected by other considerations such as: attenuation of the fiber, the wavelengths of available sources, and detector responsivity. Both graded-index and step-index fibers use the two methods of reducing dispersion, but in slightly different ways.

Step-index multi-mode fibers consist of a homogenous core of uniform refractive index (n_1) surrounded by a cladding of slightly lower (1% of n_1) refractive index (n_2); this arrangement provides for an abrupt change in refractive index at the core/cladding interface (Figure 28). In this type of optical fiber, rays propagate at different angles and, therefore, have different transient times. In a step-index fiber at length L, light incident on the face of the fiber at an angle θ must travel a distance $L/\cos\theta$ producing the path difference. Step-index fibers consist of three types, distinguished by the materials in the cladding/core and listed in the order of increasing numerical aperture: glass-cladding/glass-core, plastic-cladding/glass-core, and plastic-cladding/plastic-core. Glass-glass fibers have the lowest NA (.20-.25) and smallest core diameter (.55μ), the latter resulting from an upper limit to the size of the original glass rod they are made from. Plastic clad silica fibers (plastic/glass) have only a slightly higher numerical aperture (.3), significantly larger core (100 to 200μ), and are cheaper to manufacture; however, optical connectors are limited as a result of the soft plastic cladding changing the fiber alignment. All plastic fibers have the highest numerical aperture (.6) and the largest core diameter (100 to 1400μ). These optical fibers were designed for the purpose of gathering light from low power, inexpensive sources, not for reducing the modal

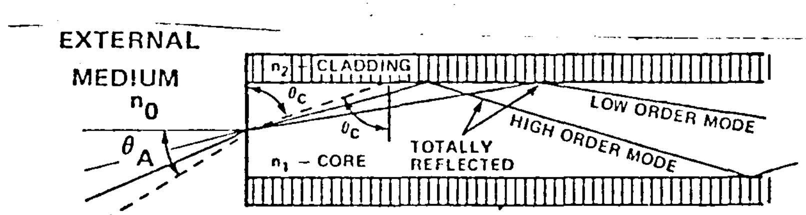


FIGURE 28
MODES OF AN OPTICAL FIBER

dispersion. In summary, step-index multi-mode fibers are limited by dispersion and are best suited for low data rate (less than 20 Mb/s) short haul (less than 1 km) data transmission systems.

Graded index fibers are distinguished from step-index fibers by their method of guiding light-distributed refraction within the core rather than internal refraction (Figure 29). This is accomplished by a gradual reduction, in a parabolic manner, of the refractive index in the radial direction from the center of the core (n_1) to the cladding (n_2). The velocity of light in a fiber varies inversely with the refractive index, light travelling faster in the lower index regions (at the outer extremities) where the path length is greater and slower in the high index region (near the optical axis of the core) where the path length is the shortest. As a result, the arrival times of all rays of light, independent of the entrance angle, are nearly the same, significantly reducing the modal dispersion. A perfectly parabolic index profile would be optimum, but mass production of commercially available fibers introduces small deviations resulting in some pulse broadening.

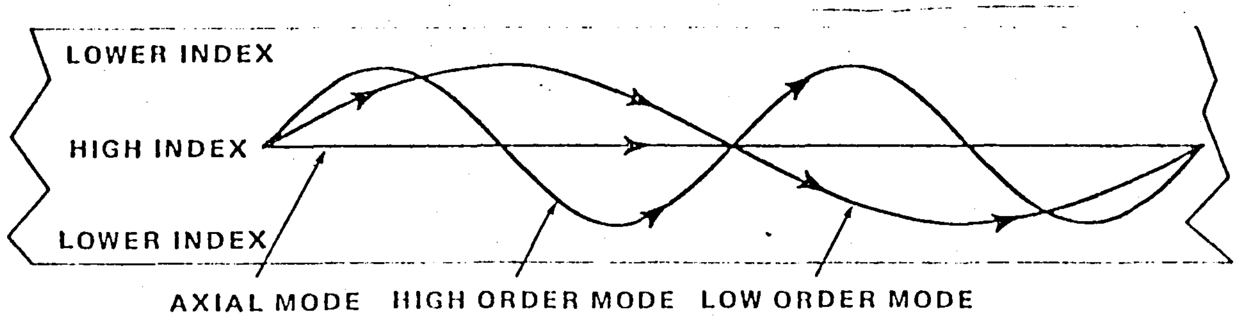


FIGURE 29
LIGHT PATHS IN A GRADED-INDEX FIBER

Another feature of graded-index fibers which differs from step-index fibers is the smaller core diameter (20 to 55μ). The smaller core diameter reduces the coupling efficiency between the source and the fiber. For short-haul transmission lines this loss of power may not be a major factor and the problem could be largely ignored. However, for long-haul transmission lines, sources producing the least divergent beams are desired. In summary, graded-index fibers

have the least temporal dispersion of the multi-mode fibers (1 ns/km) and have favorable light gathering properties when used with narrow beam sources.

Single mode step-index fibers eliminate multi-path transmission by reducing the core diameter to a point where all modes have been cut off except the fundamental mode (HE_{11}). It can be shown that υ should be less than 2.405; for an operating wavelength of .85μm and NA of .1, the core diameter should be less than 6.5μm; but for the same wavelength and NA of .2, the core diameter should be less than 3.25 μm. A major disadvantage of single-mode fibers is the source alignment problem due to the small diameter of the core, resulting in high coupling loss. The lack of modal dispersion promises high data rates, but single-mode fibers are limited to special applications where care in source-fiber alignment can be assured. A summary of the fiber types and their index profiles is shown in Figure 30.

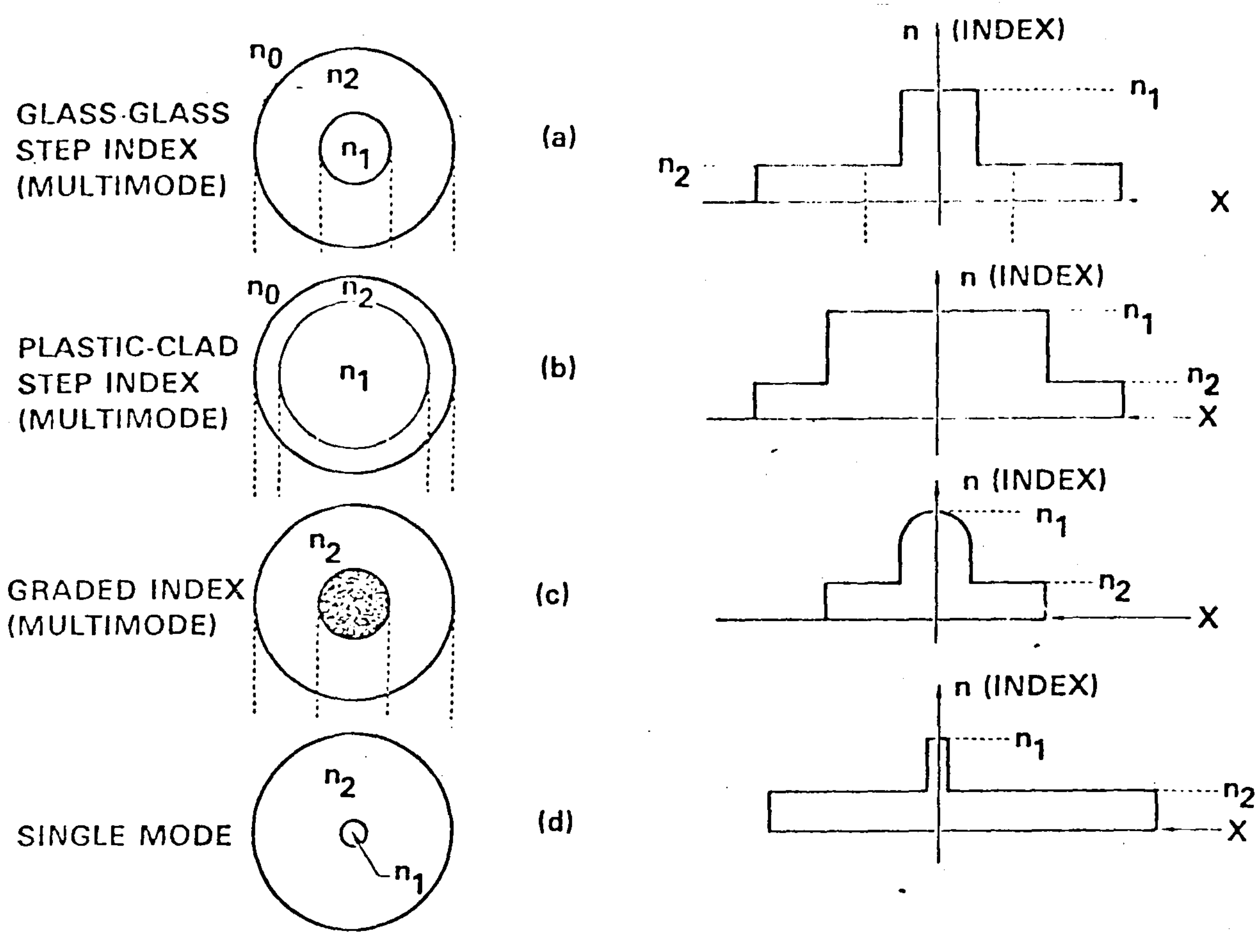


FIGURE 30 FIBER TYPES AND INDEX PROFILES

Mode coupling applies to all multi-mode fibers and actually improves dispersion by transferring energy between modes. The cause of mode coupling can be attributed to index inhomogeneity diameter nonuniformity, stresses and bending of the cabled fibers. Energy is transferred to the finite number of guided modes, improving modal dispersion effects; but also, it is transferred to the infinite number of unguided modes (radiative), resulting in losses to the cladding. Mode coupling in mono-mode fibers causes losses by transferring energy into unguided modes. As manufacturers improve the tolerances on optical fibers, the coupling of guided modes and resulting exchanges of energy between high-velocity and low-velocity modes will increase temporal dispersion closer to predicted values.

Material and waveguide dispersion is present in both multi-mode and mono-mode optical fibers. For single-mode fibers, even with narrow band sources, material dispersion is the dominant factor. Material dispersion arises from wavelength dependence on the refractive index, causing each optical wavelength to travel at a different velocity within the optical fiber. Mathematically, material dispersion depends nonlinearly on the second derivative of the refractive index with respect to the wavelength and spectral width of the source. This means wideband transmitters cause the most material dispersion, typically, 3.5 ns/km for an optical transmitter like a LED. Waveguide dispersion is a function of information bandwidth and waveguide configuration and is caused by different wavelengths for a given mode arriving at various times at the detector. Since both material and waveguide dispersion both vary with the spectral width of the source, it can be significantly reduced by using narrow band sources. Modal dispersion can be reduced by choosing an optical fiber such as graded-index.

4.1.1.3 Attenuation

Signals are not only spread in the width as they travel within an optical fiber but they also reduce amplitude as well. Manufacturers have been minimizing the effect of attenuation on optical signals by making adjustments on the glass system, glass composition, preparation and purification method, and waveguide design. Changes in manufacturing techniques and design parameters are influenced

by the following loss mechanisms: material absorption and scattering, and waveguide scattering.

Material absorption consists of three components. Losses related to the fiber material-glass or plastic are considered to be part of the intrinsic loss. Silica glass is chosen due to its negligible loss in the near infrared range; plastic is very lossy and is chosen for reasons mentioned earlier. The drawing of silica glass into optical fibers breaks SiO_2 bonds causing significant absorption losses below 740 nm. Imperfections in the atomic structure--extra or missing atoms--results in absorption losses significant only in extremely low-loss fibers. Finally, the most important, is the photoabsorption of light during interaction with impurities such as: Cu, Fe, Ni, Co, Cr, and OH since their particular bandwidths of absorption (Figures 31 and 32) fall within the range of interest. As a result, low levels of attenuation can be found at the wavelengths of 850 nm, 1060 nm, and 1270 nm.

Material scattering in silica glass, due to being an amorphous material, results from structural disorder, contamination of dust and impurities, and by random density fluctuations. Rayleigh and Mie scattering are caused by particles smaller than the operating wavelength or inhomogeneities on the order of a wavelength of light. Brillouin and Raman scattering are nonlinear, and are used to determine the upper limit of input power into a long single mode fiber where these forms of scattering are dominant. Generally, only Rayleigh scattering is considered a significant loss; it represents the lower limits of attenuation in optical fibers.

Waveguide scattering is caused by variations in the dimensions of the core along the length of the fiber. While mode coupling can reduce the effects of dispersion on optical signals, it can also cause light to be radiated into the cladding. Waveguide structure can be imperfect due to manufacturing processes, but also imperfections can arise from external considerations such as temperature variations, stress on the cable, and bending of the cable. Generally, the manufacturer should be consulted on the temperature range, the amount of stress clamps can place on the cable and the minimum bending radius of the cable.

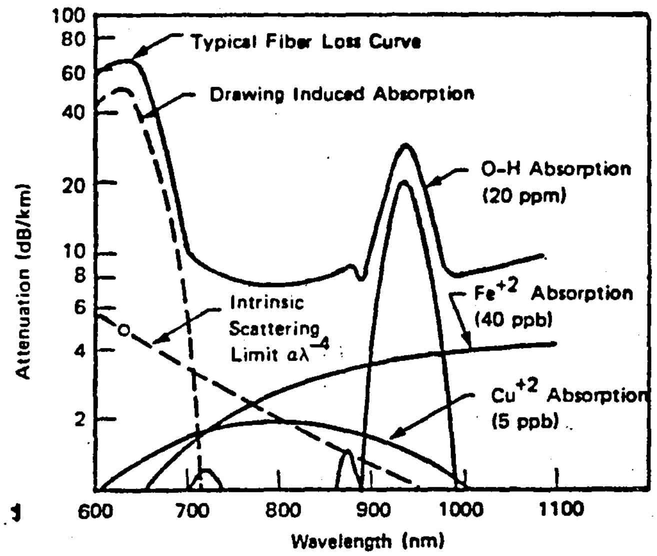


FIGURE 31
ORIGIN OF LOSS IN OPTICAL GLASS FIBERS

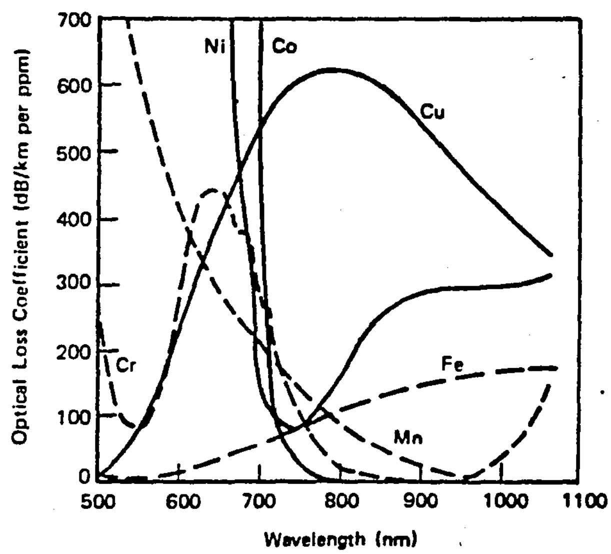


FIGURE 32
IMPURITY ABSORPTION EFFECTS

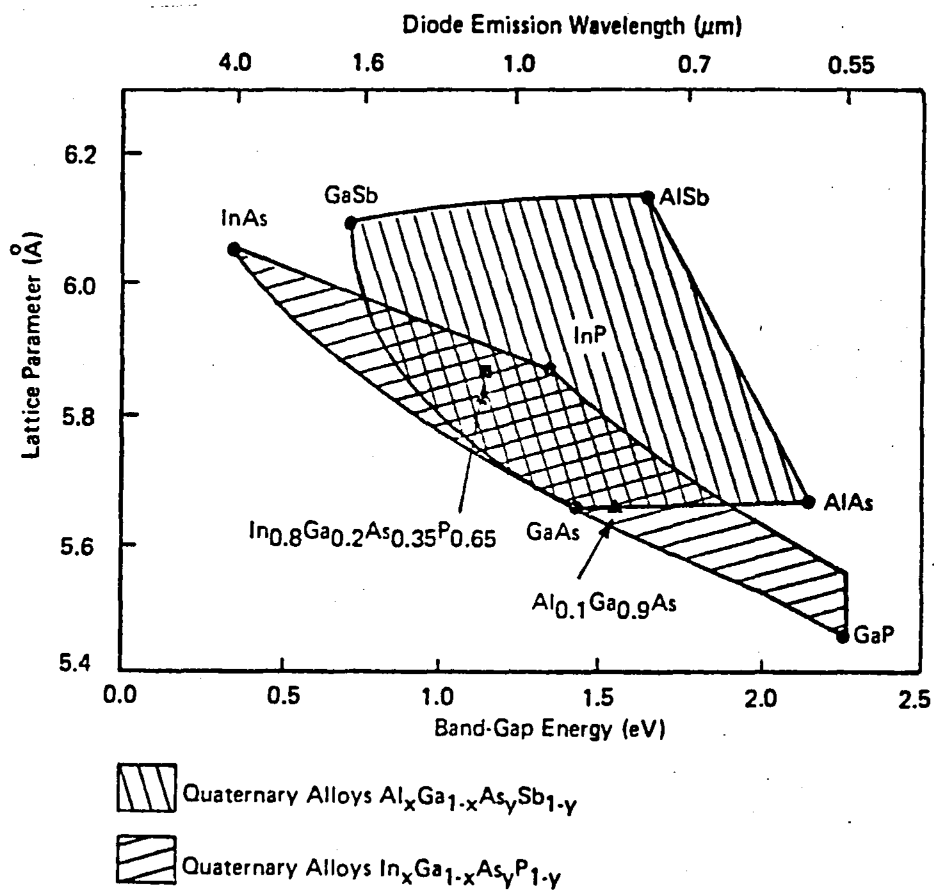
In summary, attenuation in the range of 2 dB/Km to 3 dB/Km can be obtained in premium grade fibers when sufficient control of intrinsic loss mechanisms is accomplished by manufacturers; attenuation from external effects can be kept to 2 dB extra loss when sufficient foresight in design is applied. Figure 33 makes a brief comparison of the five major types of optical fibers.

CHARACTERISTICS AND PARAMETERS	SINGLE MODE GLASS/ GLASS	GRADED INDEX MULTIMODE GLASS/ GLASS	STEP INDEX MULTIMODE GLASS/ GLASS	PLASTIC CLAD STEP INDEX MULTIMODE PLASTIC/ GLASS	PLASTIC STEP INDEX MULTIMODE PLASTIC/ PLASTIC
ATTENUATION (dB/km)	4 → 20 LOW	3→4 LOW	10→50 MODERATE	10→50 MODERATE	>100 HIGH
DISPERSION AND RISETIME (ns)	<1 ns LOW	.25 → 5 LOW	5 → 15 MODERATE	15 → 25 MODERATE	>25 HIGH
TRANSMISSION LENGTH (km)	HIGH	<10 HIGH	<1 MEDIUM	<1 MEDIUM	<.1 LOW
BANDWIDTH LENGTH (MHz-km)	>1000	200 → 1000	50 → 100	10 → 50	<10
NUMERICAL APERATURE	.1	.2 → .25	.15 → .55	2.0 → .55	.5 → .6

FIGURE 33 COMPARISON OF OPTICAL FIBERS/TYPES

4.1.2 Transmitter

To determine what constitutes a usable transmitter, the properties and characteristics of the source should be evaluated in relation to the requirements. The most important consideration is the peak output wavelength of an optical source which should be nearly identical with the wavelength at which optical fibers have the lowest attenuation. The most commonly used wavelengths are between 800 to 860 nm where a minimum occurs in attenuation for optical fibers and transmitters in this range consist of GaAsAl; the next minimum occurs at 1040 to 1060 nm and GaAlIn transmitters are used; and finally a minimum occurs between 1200 to 1300 nm where InGaAlP transmitters operate (Figure 34). The optical power should be high enough to meet the requirements of the system (BER, detectability, variations in losses during lifetime) without overheating the device, causing either gradual or abrupt degradation. To reduce the



Area Boundaries Represent Ternary Alloys; Vertices Represent Binary Alloys.

Source: *Physics Today*, May 1976, p. 40.

FIGURE 34 LATTICE PARAMETERS AND ENERGY GAPS OF VARIOUS III-V ALLOYS

coupling loss, the output directivity of the beam pattern should coincide with the fiber's acceptance cone. The output spectral bandwidth should be narrow enough to meet the material dispersion limitations and the transmitter rise time should be low enough to meet modal dispersion requirements imposed by the data rate. Adverse thermal effects on the source, produced by operation at high current densities and high operating temperatures, can cause a reduction in the light output and should be avoided. The lifetime of the device should be well known in terms of the environmental and operating conditions. Output distortion should be consistent with either a digital or analog format, the latter requiring a more linear relation between output power and drive

current. Each of the above parameters shall be discussed in relation to the two most commonly used transmitters for optical fiber transmission: light-emitting-diodes (LED) and injection laser diodes (ILD).

4.1.2.1 LED

Generally, LEDs are designed by sandwiching a thin active layer of gallium arsenide between two layers of GaAlAs which do not absorb energy, but act as light guides. Thus, this design which forms the P-N junction is called a double-heterojunction structure. After the LED is switched-on, carriers are injected across the P-N junction; those that are not absorbed recombine to generate light. The rate of recombination sets the upper limit on how fast the LED may be pulsed, with the best devices transmitting data up to 50 Mb/s. By increasing or decreasing the aluminum content, the output wavelength may be varied from 780 to 860 nm. The quantum efficiency, defined as the ratio of emitter photons to injected carrier pairs, usually remains constant throughout the wavelength range of operation. Longer wavelength transmitters (1060 nm and 1270 nm), similar in structure and internal operation, find slightly lower attenuation in optical fibers (1 to 1.5 dB/km) in this range of wavelengths, but also a much lower responsivity in photodetectors. LEDs of longer wavelengths do not, as yet, meet the power outputs of GaAsAl LEDs, and as a result cannot take advantage of the lower attenuation of optical fibers and overcome the lower responsivity of detectors. Therefore, they must be excluded for the near-term approaches, but make promising candidates for the long-term approaches as their output increases and new detectors are developed.

LEDs can be classified according to material composition, but they can also be classified according to the configuration of the P-N junction and the direction in which the light is emitted, whether it is at the surface or at the edge. Planar and dome LEDs are large area surface emitters and, as a result, their narrow emission angles do not compensate for the poor efficiency in which their output power is coupled into a single fiber. The Burrus LED (Figure 35), the most important of the surface emitters, produces a broad beam (45 degrees) but due to the small emitter size, most of the light is concentrated near the axis of the fiber, making them especially compatible with graded-index fibers. The

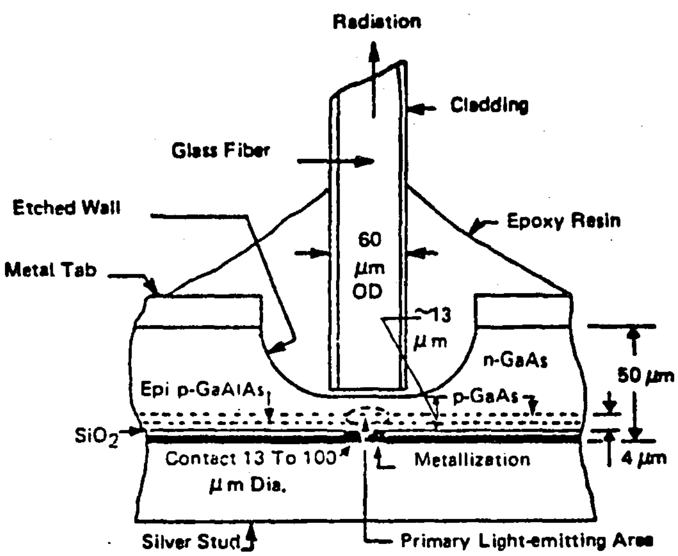


FIGURE 35 BURRUS LED

Burrus LED has constructed within the substrate a small circular emitting section (150 microns in diameter) at the bottom of an etched well; this configuration reduces coupling loss by allowing a single fiber to be closely butted against the emitting area. These devices have been thoroughly tested at room temperature, at elevated temperatures and during temperature cycling; for example, no change in efficiency was noted over a temperature range of -40C to +80C during 20 cycles. Finally, Burrus diodes have relatively fast rise times resulting in digital and analog modulation with bandwidths over 50 MHz, and can be operated in a high duty cycle. It has been concluded that these devices have reached a theoretical maximum efficiency (45%) and output power of 7 mW; however, reliability and lifetime will continue to increase, probably reaching one million hours. Edge-emitters (Figure 36) generate light on all four sides with guiding layers channeling the light to produce a narrow beam, hence, reduced coupling (NA) losses. Nevertheless, edge-emitters also produce less optical power and have a much larger emitting area than Burrus LEDs. Another characteristic of edge-emitters is the emission of light from all four sides causing a loss in the efficiency of the light generation to light coupled into the fiber, unless a way can be found to gather all the light and focus it into the fiber. In summary, the Burrus diode couples the most light into an optical fiber of all the surface emitters and the edge emitter.

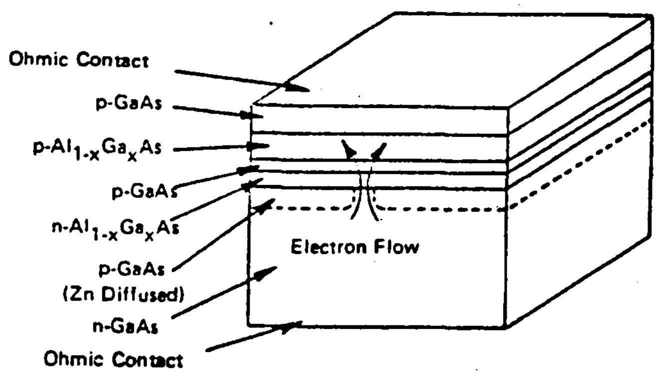


FIGURE 36 EDGE-EMITTING DIODE

In general, LEDs have a number of properties which are characteristics of all types of LEDs. LEDs require simple drive circuits and low drive currents (50 to 200 ma). The light output is nearly a linear function of the drive current--the requirement for low harmonic distortion in analog systems. Also, variations in the drive current do not noticeably affect the peak emission wavelength and half power spectral width. Wide bandwidth sources cause chromatic dispersion, the spreading of a pulse due to the different velocities of the spectral components, and limit the bandwidth of the system. The spectral half width of a typical LED is between 35 to 45 nm centered at 840 nm. The risetime of a source influences the modal dispersion of a pulse by spreading the pulse in time. LEDs have been fabricated with risetimes of between 3 to 7 nanoseconds by lowering the device capacitance, although, 10 ns and above is more common. For all the LEDs, the light output power dependence on temperature is relatively low (.2%/C). Presently, reliability is high with lifetimes exceeding 100,000 hours. The small size of the LEDs have led source and connector manufacturers to consider placing them inside the connectors; as yet, only single optical connectors are available with LEDs, but within two years it is expected a wide variety of multi-channeled connectors can be outfitted with LEDs. Obviously, mating electrical circuit must be compatible with the drive circuits of the LEDs. Reaching maximum power outputs, as much as 7 mW of uncoupled power, and the Lambertian beam pattern of LEDs have caused manufacturers to seek techniques for increasing the coupled power into the fiber.

Before discussing the techniques employed to increase coupling efficiency, the method of calculating the magnitude of the coupling loss should be examined since the designer may not be able to obtain a single number for the input power to a particular fiber. The magnitude of input coupling loss depends on the physical characteristics of the source and the fiber; significant parameters are emitting area, fiber core area, and separation between the emitting surface and the fiber end; losses result from area mismatch between the sources illumination spot (in the plane of the fiber end) and the core. Also, the magnitude of the input coupling loss depends on the optical characteristics; the important parameters are angular emission profile, numerical aperture, and refracted index; variations of these parameters can result in losses generated from light rays leaving the LED with wider angles of incidence than the fibers acceptance cone and from light reflected back off the fiber end. Losses from unintercepted illumination results from sources emitting surface area being larger than the fiber core area. Separation of source and fiber can allow light to pass by the core, even when the source emitting area is smaller than the core area. The magnitude of the area mismatch coupling loss is:

$$\text{UI Loss} = 10 \log \left[\frac{\text{Area of the core}}{\text{Area of projected optical spot in the plane of the fiber core}}\right]$$

In order to understand numerical aperture loss, it is necessary to be able to calculate the input coupling efficiency by mathematically describing the source-beam profile. A polar diagram is used to plot radiant intensity against angle of emission from data obtained from a detector moving through a 180° arc. A Lambertian emission power profile (Figure 37) may be expressed mathematically as:

$$P = P_0 (\cos\theta)$$

while a narrower beam pattern (Figure 38) can be approximated by:

$$P = P_0 (\cos\theta)^m$$

Either by matching or interpolation the pattern supplied by the manufacturer can be compared to Figure 38 to obtain "m". To determine the coupled power (P_c) the following equation can be used:

$$P_c = P_T [(1 - \cos\theta)^{m+1}]$$

where θ is the angle of the acceptance cone and "m" is obtained from the method described above. Some source manufacturers simply supply a curve relating the acceptance-cone angle to the percentage of the total radiant flux.

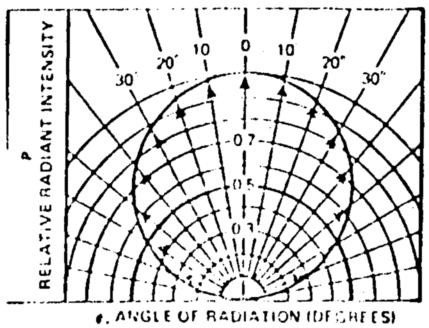


FIGURE 37
LAMBERTIAN PATTERN

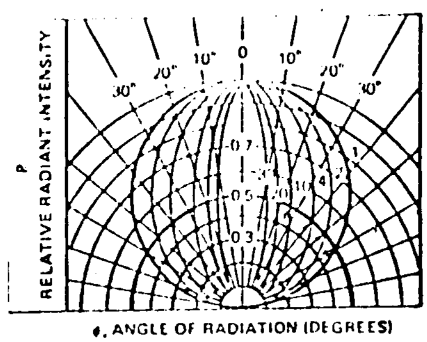


FIGURE 38
NARROWER BEAM PATTERNS

Reflection loss is generally smaller than numerical loss and area mismatch loss except in fiber splices where it is the dominant factor. The difference in the refracted index between the air and the glass causes some of the incident light to be reflected off the core of the fiber; the fraction of the incident light P, the reflection coefficient, is approximated by an equation derived from the Fresnal equations:

$$P = \left[\frac{(n_1 - 1)}{(n_1 + 1)}\right]^2$$

The reflection loss can be expressed as:

$$L_R = 10 \log (1 - P)$$

Using an example, the small loss from reflection can be appreciated--assume core index of 1.45, P - 3.4% and the loss = -.15 dB.

Manufacturers of sources have been attempting to find ways of reducing coupling loss by adding devices to the LED rather than changing the structure of the LED. One way of reducing the coupling loss is to add an epoxy-attached section of an optical fiber--called a "pigtail"--to the LED. The pigtail is precisely aligned to optimize the coupling, and then butted against the emitter surface; the separation between the fiber and the emitter should be less than 3 times the core diameter. Another method of improving coupling efficiency is to use a lens to collimate the rays of the light. An LED is placed at the focal length of the lens with another lens used to refocus the light into the fiber. Reflecting surfaces are sometimes used to gather all the light from the edge emitters since they produce light on all four sides. If the designer asks the manufacturer to supply an LED with lens or "pigtail" or both, then the manufacturer should be able to provide a single coupling loss number.

4.1.2.2 Lasers

Semiconductor laser diodes can be best described by comparing their physical and optical characteristics with LEDs. The physical characteristics of Injection Laser Diodes (ILD) are roughly similar to LEDs; physical size (10 mils on a side) and an active emitter region (1 x 20 microns) are much smaller. The materials used to construct ILDs are the same and the resulting range of operating wavelengths are approximately equal; for example, GaAsAl lasers have an operating range of 800 to 900 nm. Like LEDs, ILDs commonly use "pigtails" and occasionally lenses to improve coupling efficiency. The actual configuration of the ILD is roughly similar to the LED with the stripe double-heterojunction laser diode (Figure 39) being the most commonly used laser type.

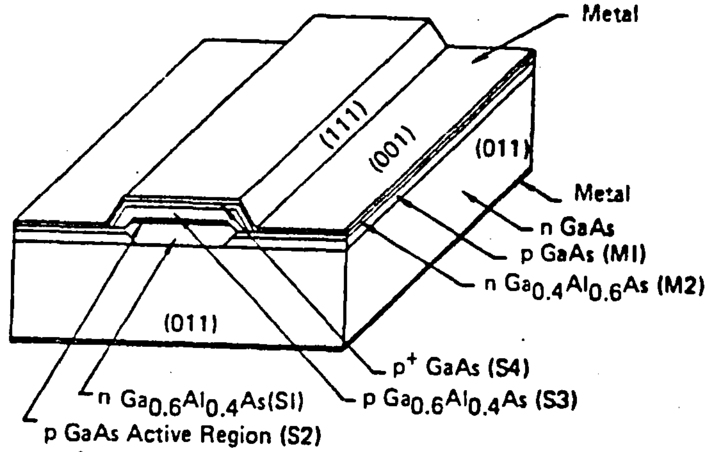


FIGURE 39
LASER DIODE

The optical characteristics of the ILD generally contrast with the LED, falling into two categories: advantages and disadvantages of lasers over LEDs. Spectral bandwidth is a major contributor to material dispersion: ILD diodes have a typical bandwidth of 2 to 4 nm while LEDs have bandwidths of over 30 nm. The emitted beam pattern of an ILD is far more directional than an LED, configured in the shape of an ellipse with the broad part perpendicular to the junction (20° to 45° half angle) and the narrower part (10° to 15°) parallel to the junction. The non-Lambertian radiation pattern results in a narrower beam which is more easily coupled into a fiber, generating coupling losses of only 2 to 5 dB rather than 6 dB or more for LEDs. In contrast, the quantum efficiency is lower for an ILD (20-40%) since too high an efficiency would make the laser diode difficult to control. Emission from an ILD is stimulated while emission from an LED is spontaneous giving rise to higher modulation frequencies (greater than 1 GHz). Risetimes for ILDs have begun to drop below 1 nanosecond, while LEDs have remained above 3 nanoseconds. This makes ILDs well suited for digital modulation, but analog modulation depends on the ILD being operated above the threshold for lasing, suppression of second and third harmonics, and careful modulation along the steep linear slope of the drive current to input power curve.

The two disadvantages of Injection Laser Diodes (ILD) are a lower lifetime and more sensitive temperature dependence. The lifetimes of ILDs tend to be shorter than LEDs, unless the latter is operated at the highest power output of the devices. Nevertheless, it cannot be said with certainty that laser diodes will not catch up with LEDs in this regard. ILD lifetimes have reached 100,000 hours and may reach 1,000,000 hours in a few years. Allowing the temperature to vary has profound effect on the lifetime of the laser diode. A fast drop in temperature could damage a facet as a result of the steep drive current vs power output curves; however, rise in temperature could cause the threshold drive current for lasing to rise above the operating drive current. One temperature compensation technique is to use a feedback circuit to monitor a laser output in order to maintain a constant drive current above threshold. Another method, more commonly employed, is to mount the laser diode on a small thermo-electric heat pump, maintaining the ILD at a fixed temperature. In conclusion, the advantages of laser diodes make them attractive for the present application and the disadvantages can be overcome.

Figure 40 compares the two semiconductor sources (LED, ILD) against each other and against a nonsemiconductor source (Nd:YAG) to illustrate their similarities and differences. The nonsemiconductor source was not discussed, since the options for its use were not selected for further investigation.

4.1.3 Photodetectors

This section describes the qualities of photodetector diodes which make them attractive for optical fiber communications and the parameters used to measure their performance. Then the two most frequently used photodetectors--PIN and APD--are described in terms of those parameters.

4.1.3.1 Performance Guidelines of a Photodetector

A photodetector should have certain qualities in order to perform its primary purpose of detecting weak light signals, converting them to electrical signals, and amplifying them to usable levels. The efficiency of converting light to electricity should be high at the operating wavelength. The conversion of input power to electrical power should be linear throughout the dynamic range

of the receiver. The response time should be fast. The bandwidth of the photodetector should be equal to or greater than the information bandwidth. Photodetectors should contribute as little noise as possible to the signal and have low dark currents. The photodetector output should remain constant in respect to environmental variations (temperature, humidity, radiation). Finally, the photodetector should be constructed for reliability, easy coupling to optical fibers, and compatibility to mating electronic circuits.

CHARACTERISTICS AND PARAMETERS	LIGHT EMITTING DIODES LED	INJECTION LASER DIODES ILD	LASER NONSEMI CONDUCTOR
MATERIAL AND WAVELENGTH	GaAsAl .8-.9 μm GaAlIn 1.04-1.06 μm InGaAlP 1.2-1.3 μm	GaAsAl .8-9 μm InGaAlP 1.2→1.3 μm	Nd-YAG 1.0→3.0 μm
TYPE OF LIGHT EMITTED	INCOHERENT MULTIMODE	NEARLY COHERENT NEARLY SINGLE MODE	COHERENT SINGLE MODE
SPECTRAL WIDTH	20 → 60 nm	1.5 → 3.0 nm	<0.5 nm
RISETIME	5 → 15 ns	.5 → 2 ns	---
BANDWIDTH	10-150 MHz	200-1000 MHz	500-2000 MHz
LIFETIME	10^5 HR	10^5 HR	10^4 HR
LINEARITY	HIGH	MEDIUM	LOW
REMARKS	BURRUS DIODES PRODUCE HIGHEST POWER	ADJUSTABLE LINEARITY AND HARMONIC DISTORTION STRIPE DOUBLE HETEROJUNCTION GIVES BEST PERFORMANCE	REQUIRES EXTERNAL MODULATOR DUE TO LONG RISE/ FALL TIMES

FIGURE (40) COMPARISON OF OPTICAL TRANSMITTERS TYPES FOR FIBER OPTICS

There are several parameters used to quantitatively describe photodetectors in terms of the aforementioned qualities which need to be defined. The term responsivity (R) describes the sensitivity of the photodetector. It is the ratio of the receiver output in terms of either current (amps) or voltage (volts) to the radiant input flux (ϕ) of the receiver in watts. When the radiant flux is for a band of wavelengths, the signal current is given by:

$$I_S = R\phi$$

The quantum efficiency is defined as the ratio of absorbed photons to the photoelectrons emitted; a unity quantum efficiency implies one electron for every absorbed photon. For a particular wavelength, the quantum efficiency can be defined as:

$$n(\lambda) = \frac{\text{number of photoelectrons/second}}{\text{number of absorbed photons at a certain wavelength/second}}$$

The quantum efficiency can be related to the responsitivity by:

$$n(\lambda) = \frac{hc}{e}\frac{R(\lambda)}{\lambda} = \frac{1.24\ R(\lambda)}{\lambda}$$

with λ in units of microns. The gain of the detector is not included. The quantum efficiency in the above equation depends on many parameters: wavelength, modulation, operating temperature of the detector, of the photodetector, and geometry of the detector.

Several parameters are used to describe the noise in a photodetector, consisting of a dark current, shot noise and thermal noise. The dark current (i_d), measured in nanoamps, is internal to the photodetector and flows regardless of the absence of signal or background radiation. The noise current represents fluctuations in the signal which are a function of the random arrival of photons (shot noise) at the detector, and the thermal motion of the charge carriers (johnson noise) within the coupling resistor and noise generated by the amplifier. Therefore, the signal-to-noise ratio can be defined as the signal current to noise current:

$$\frac{S}{N} = \frac{\overline{i_S^2}}{\overline{i_{SH}^2} + \overline{i_j^2}}$$

The mean square shot noise is:

$$\overline{i^2}_{SH} = \frac{3e^2(P + P_B)\eta\Delta\nu}{h\nu} + Z\ e i_d \Delta\nu$$

The mean-square johnson noise is:

$$\overline{i^2}_{S} = \frac{4K^{T}e}{R_L}\Delta\nu$$

Where P is the signal power; $\Delta\nu$ is the modulation frequency; P_B is the background power; i_d is the dark current; h is Plank's constant; e is the electronic charge; and R_L is the load resistance. If the load resistance is small enough and P is near the minimum detectivity then:

$$\frac{S}{N} \cong \frac{2(Pe\eta/h\nu)^2}{4KT_e\Delta\nu/R_L}$$

The noise equivalent power (NEP) is the radiant flux (watts) incident on the detector which gives a signal-to-noise ratio equal to one.

Setting S/N = 1 and solving for P

$$NEP = (P)\min = \frac{h\nu}{e\eta}\sqrt{\frac{2KT_e\Delta\nu}{R_L}}$$

or

$$\frac{NEP}{\sqrt{\Delta\nu}} = \frac{h\nu}{e\eta}\sqrt{\frac{2KT_e}{R_L}}$$

with T_e = effective noise temperature. The second equation gives the NEP normalized to any modulation frequency. The detectivity of a photodetector is the reciprocal of the NEP, but does not provide a measure of comparison between photodetectors of different detector area (A) and bandwidth (B). Therefore, the specific detectivity is defined as:

$$D_{SP} = \frac{\sqrt{AB}}{NEP} = D\ \sqrt{AB}\ \ (\mathrm{Cm\ Hz}^{\frac{1}{2}}\ \mathrm{W})$$

4.1.3.2 Pin

The P-I-N (position-intrinsic-negative layers) diodes are composed of silicon, germanium, GaAs, and InGaASP; all of these materials have absorption coefficients that are dependent on wavelength (Figure 41). Silicon is used for operating wavelengths of 800-1000 nm and is the most commonly used material in photodetectors because of its high sensitivity, wide bandwidth and low noise. Germanium has good absorption properties up to 1600 nm, but due to its unusually high dark current, it is only considered in regions--1000 nm to 1100 nm--where other detector materials have low sensitivity. Long wavelength transmitters (1200 to 1300 nm) composed of InGaASP have given rise to research into the same materials for detectors. So far, the development of long wavelength photodetectors has not kept up with the advancing technology of long wavelength transmitters. Therefore, silicon detectors offer the best match to transmitters operating between 800 and 900 nm.

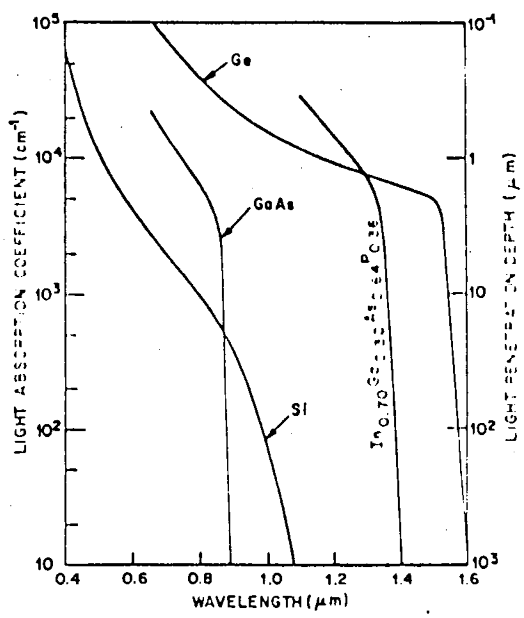


FIGURE 41
OPTICAL ABSORPTION COEFFICIENT VS. WAVELENGTH
FOR COMMON DETECTOR MATERIALS

PIN diodes, made from silicon, are packaged so that light enters through a window, with an antireflection coating, slightly larger than the fiber core for good coupling (<1 dB). Making the active surface area larger to accommodate larger core fibers has two negative effects: the first is to increase the dark current, and the second is to increase the capacitance which increases the response time of the detector. A balance can be obtained by using small core graded index fibers; hence, the dark current can be kept roughly equal to 1nA and the capacitance to 2pF; therefore, the rise time should be in the range of nanosecond.

Light is absorbed in a thick intrinsic region (depletion layer) of high quantum efficiency (Figure 42). If the incident photon energy ($h\nu$) is greater than the bandgap of the semiconductor materials, then electron-hole pairs are produced. A uniform electric field, produced by a reverse-bias voltage supply, separates the electrons and holes, causing them to drift in opposite directions. Increases in the reverse bias voltage can thicken the depletion layer causing the responsivity to increase: voltages below 50 V have associated responsivities between .4 and .55 A/W, while voltages above 50 V have responsivities between .5 to .7 A/W. Also, PIN diodes with voltages between 50 to 100 volts have higher dark currents, and perhaps, shorter life times. The junction capacitance is related to the thickness (w) of the depletion and the area of active region (A) by:

$$C_j = \frac{eA}{\omega}$$

Thus, the bias voltage is also connected to the speed of the device. Charge carriers are accelerated by the electric field through the depletion region to very high velocities (10^7 cm/sec); the transit time is calculated by multiplying the average velocity by the width of the depletion region. The depth of the depletion region also determines the quantum efficiency; therefore, changes in the response time may have adverse affects on the quantum efficiency. The transit time, coupled with the $1/R_L C_j$ constant, determines the response time (risetime), which is usually on the order of a nanosecond for fast PIN diodes. The RC constant is composed of the junction capacitance ($1 \rightarrow 5$ pf), and the equivalent resistance (composed by the load resistance and feedback resistance).

Furthermore, the modulation frequency is limited by the RC constant

$$\omega << \frac{1}{R_L C_j}$$

In conclusion, PIN diodes have low rise times (1ns), high quantum efficiencies (80-90%), life time of 10^5 hours and a wide dynamic range of 8 to 10 orders of magnitude, making them useful for moderate to high bandwidth systems; but their low responsivity (.4 to .7 A/W) requires strong optical signals.

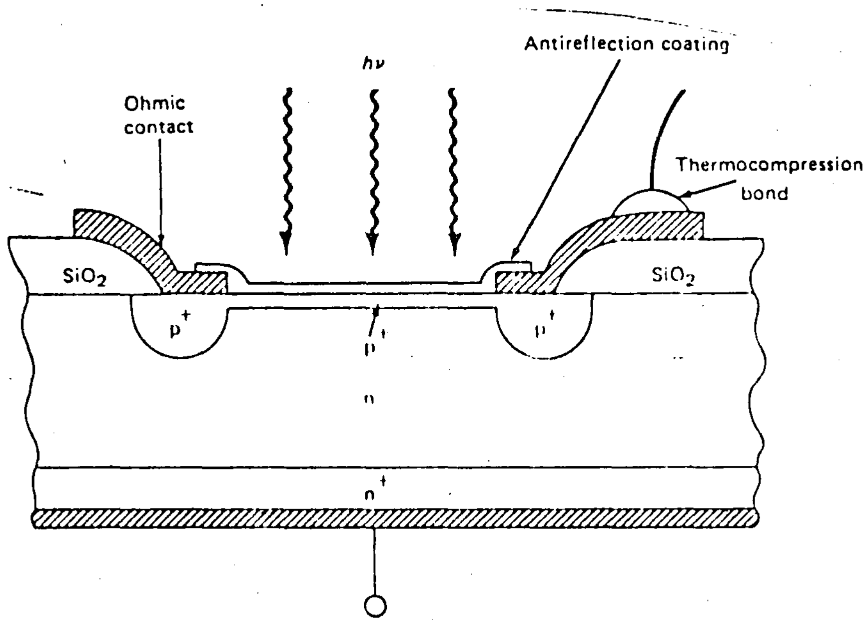


FIGURE 42
GUARD RING PHOTODIODE

4.1.3.3 APD

The Avalanche Photo Diode (APD) has the small size of the PIN and the built-in avalanche gain mechanism of the photomultiplier tube. It basically functions like a PIN diode, except the higher applied voltage produces a stronger and nonuniform electric field (Figures 43 and 44). Charge carriers produced by photoabsorption are accelerated with enough energy to generate secondary charge carriers by impact ionization. More electron pairs are produced until their energy is dissipated below the energy required for further impact ionization. The multiplication factor is equal to:

$$M = \frac{1}{1 - [(V_a - IR_s)/V_B]^n}$$

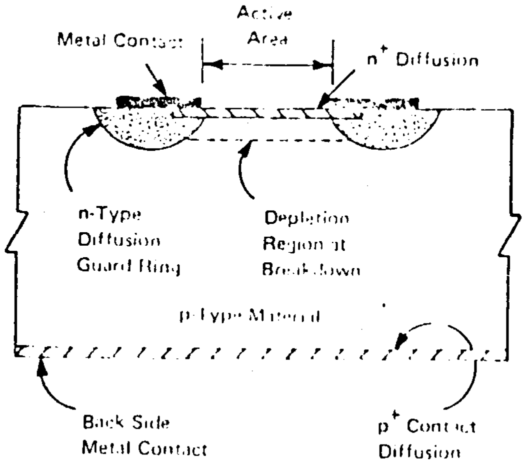


FIGURE 43
GRADED GUARD-RING APD

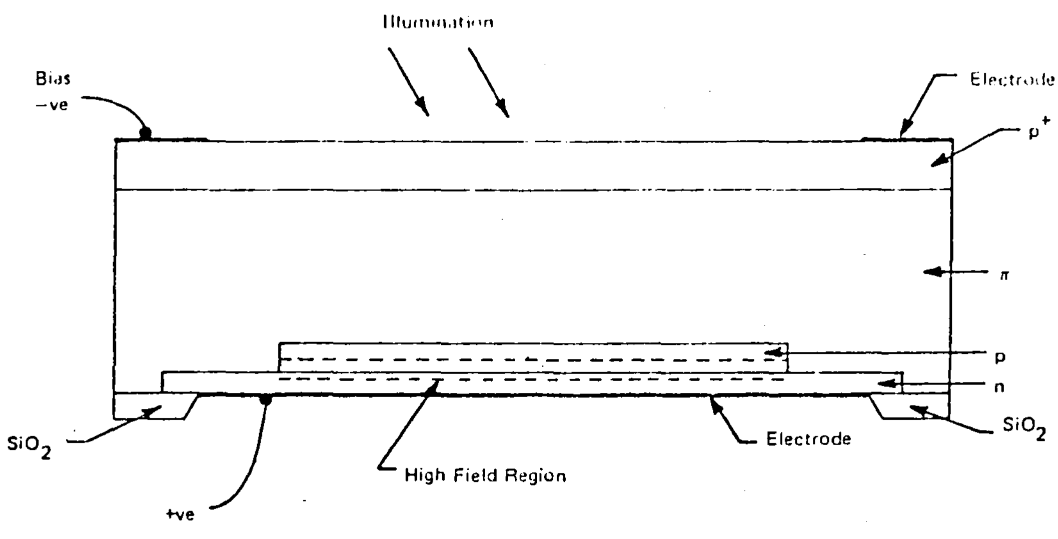


FIGURE 44
DOUBLE-DIFFUSION
REACH-THROUGH STRUCTURE

where V_a = applied bias voltage

I = output current

R_s = effective series resistance

V_B = breakdown voltage

n = constant depending on material used and wavelength of light

APDs are made out of silicon and germanium with silicon capable of producing higher gain and less noise.

The higher gain of the APD has both positive and negative effects on the parameters of the photodetectors. Responsivity, a measure of the electric current generated per unit of incident power, is increased to as much as 75 A/W. As a result, the APD can provide the same performance with 20 dB less incident optical power. The disadvantage is the multiplication factor applies to the incident optical noise and the dark current (0 to 20 nA) as well. However, in wideband applications (>1 MHz), the noise of the preamplifier and not the noise from the detector dominates. To maintain a constant gain, the APD requires a highly regulated power supply and a constant temperature chamber. Changes in the gain may not greatly affect a pulse-code modulated system where the absolute value is the only concern, but could cause problems in the analog-modulated system. Lifetime for the APD appears to be only slightly less than PIN diode (10^5 hours).

In conclusion, the advantage of an APD over a PIN diode applies only in the case of weak signals; otherwise, the two photodetectors are roughly commensurate, since the limiting factor for strong optical signals is the quantum noise of signal. A complete comparison of the two photodetector diodes is shown in Figure 45.

4.2 POWER MARGIN AND DISPERSION ANALYSIS

Using the information from the previous section on optical components and the requirements section, the losses and risetimes of the two payload communication links are totaled and compared to the data rate and BER requirements.

CHARACTERISTICS AND PARAMETERS	PIN DIODE DETECTORS SILICON	ADP DETECTORS SILICON
SENSING AREA FOR COUPLING	.3 → 3 mm	.8 → 8 mm
SENSITIVITY AT 1 MHz	-55 dBm	-70 dBm
DYNAMIC RANGE	60 dB	20 dB
BANDWIDTH	50 → 300 MHz	75 → 1000 MHz
RESPONSIVITY AT PEAK WAVELENGTH	.4 → .7 A/W	10 → 70 A/W
RISETIME	1 → 10 ns	2 → 10 ns
QUANTUM EFFICIENCY	.80 → .95%	.30 → .90%
DARK CURRENT	1 → 50 nA	5 → 100 nA
LIFETIME	10^5 HR	10^5 HR
BIAS VOLTAGE	10 → 50 V	200 → 350 V

FIGURE 45 COMPARISON OF OPTICAL PHOTODETECTORS TYPES FOR FIBER OPTICS

4.2.1 Payload Checkout Link

The dispersion analysis and power margin are calculated for both a 300 Mb/s (max) and 50 Mb/s (max) optical communication system, thereby, covering three out of the four options. A system capable of transmitting high data rates over short distances (200 m) typically consists of an ILD, graded index fibers, and a PIN diode. A system capable of transmitting 50 Mb/s or less and an optical source small enough to be placed internally to an optical connector, typically consists of a LED, instead of an ILD (ILD and ancillary components would be too large, Section 4.1.1.3), and is connected to a common optical cable and PIN diode.

First, consider the dispersion analysis of an optical system capable of transmitting up to 300 Mb/s. This system is composed of two optical connectors on

a 200 m optical cable, PIN diodes and ILDs. As shown in Figure 46, for NRZ data transmitting at 300 Mb/s, the total rise time must be less than 2-3 ns. This can be accomplished by selecting graded index fibers (1 ns/km), relatively fast PIN diodes (1 ns), and an ILD with a rise time of less than 1 ns. For the LED/PIN optical link (Figure 47, assuming a common cable and PIN diodes, the required rise time is 14 ns, which is well above the calculated system rise-time. RZ data (Manchester II code) would also be compatible with this system, since the rise time would be 7 ns (half NRZ). Therefore, the modulation rate of the LED is not limited by the rise time of the device, but by the loss of power and reduction of lifetime at higher data rates. Given those limitations, it is possible to push LEDs up to 50 Mb/s.

The power margin analysis for both approaches shows that the attenuation would be roughly the same (Figures 48 and 49); the LED/PIN system may require only 1 dB loss for a single connection (average loss for optical connectors and glass-glass fibers) due to the direct connection of optical fiber to LED within an optical connector. The average source power for the LED, including coupling loss, is -10 dBm. The receiver sensitivity for a PIN diode at 10^{-8} BER is:

PIN sensitivity = 10 log D - 55

Where D is the data rate in Mb/s. The receiver sensitivity at 50 Mb/s is:

PIN sensitivity = 10 log 50 - 55 = 38 dBm

The average source power from the optical "pigtail" of an ILD is 0 dBm and the receiver sensitivity for PIN diode (same as used before) at 300 Mb/s is:

PIN sensitivity = 10 log 300 - 55 = 30 dBm

In conclusion, the power margin analysis shows attenuation restrictions are not very severe, but the dispersion requirements put limitations on the optical fibers and receivers if they are used for both approaches, or could be significantly relaxed, resulting in less expensive components, if they are not.

	Present	Future Expectations
RISETIME OF OPTICAL FIBERS (1 ns/Km)	0.2 ns	.1 ns
RISETIME OF ILD	0.7 ns	.5 ns
RISETIME OF PIN	1.0 ns	1.0 ns
TOTAL RISETIME OF SYSTEM	1.9 ns	1.6 ns

REQUIRED DATA RATE 300 MB/S

FOR NRZ $\frac{.70}{300 \text{ MB/S}} = 2.3$ NS

RISETIME OF SYSTEM IS LESS THAN REQUIRED RISETIME

FIGURE 46 RISETIME ANALYSIS FOR PAYLOAD CHECKOUT LINK USING ILD/PIN

	Present	Future Expectations
RISETIME OF OPTICAL FIBERS (1 ns/Km)	0.2 ns	.1 ns
RISETIME OF LED	5.0 ns	3.0 ns
RISETIME DUE TO MATERIAL DISPERSION (4 NS/KM)	0.8 ns	.5 ns
RISETIME OF PIN	1.0 ns	1.0 ns
TOTAL RISETIME OF SYSTEM	7.0 ns	4.6 ns

REQUIRED DATA RATE 50 MB/S

FOR NRZ $\frac{.70}{50 \text{ MB/S}} = 14$ ns

RISETIME OF SYSTEM IS LESS THAN REQUIRED RISETIME

FIGURE 47 RISETIME ANALYSIS FOR PAYLOAD CHECKOUT LINK USING LED/PIN

	AMOUNT OF LOSS (dB)	FUTURE EXPECTATIONS (dB)
CONNECTOR LOSS (1 dB/CONNECTOR)	2	1
OPTICAL FIBER (200 m) LOSS (5 dB/Km)	1	1
RECEIVER COUPLING LOSS	2	1
TEMPERATURE DEGRADATION	2	2
TIME DEGRADATION	3	2
TOTAL ATTENUATION	10 dB	7 dB
AVERAGE SOURCE (LED) POWER P_S	-10 dBm	-5 dBm
RECEIVER SENSITIVITY (PIN) P_R	-38 dBm	-40 dBm
TOTAL MARGIN (P_S-P_R)	28 dBm	-35 dBm
EXCESS POWER (TOTAL MARGIN - TOTAL ATTENUATION)	= 18 dB	= 28 dB

FIGURE 48 POWER MARGIN ANALYSIS FOR PAYLOAD CHECKOUT LINK USING LED/PIN (50 MB/S) AT 10^{-8} BER

	AMOUNT OF LOSS (dB)	FUTURE EXPECTATIONS (dB)
CONNECTOR LOSS (1 dB/CONNECTOR)	2	1
OPTICAL FIBER (200 m) LOSS (5 dB/Km)	1	1
RECEIVER COUPLING LOSS	2	1
TEMPERATURE DEGRADATION	2	2
TIME DEGRADATION	3	2
TOTAL ATTENUATION	10 dB	7 dB
AVERAGE SOURCE (ILD) POWER P_S	0 dBm	5 dB
RECEIVER SENSITIVITY (PIN) P_R	-30 dBm	-35 dBm
TOTAL MARGIN (P_S-P_R)	30 dBm	40 dBm
EXCESS POWER (TOTAL MARGIN - TOTAL ATTENUATION)	= 20 dB	33 dB

FIGURE 49 POWER MARGIN ANALYSIS FOR PAYLOAD CHECKOUT LINK USING ILD/PIN AT 300 MB/S AT 10^{-8} BER

4.2.2 Payload Monitoring Link

The optical link, carrying payload data (Option B), connecting the Mobile Launcher Platform with the pad and the LCC is both power and dispersion limited. For this reason, to send the maximum data rate requires NRZ data. NRZ data allows twice the data rate but requires the clock to be sent on a separate optical fiber, apparently cancelling the higher data rate. However, by multiplexing two different wavelengths of sufficient separation through the same optical fiber, there would be no net increase in the number of fibers. The method of duplexing two optical wavelengths is shown in Figure 50. The total loss for each channel consists of a total of 4 dB loss due to fusing of two optical fibers into one single fiber and a 3 dB loss due to the division of optical power.

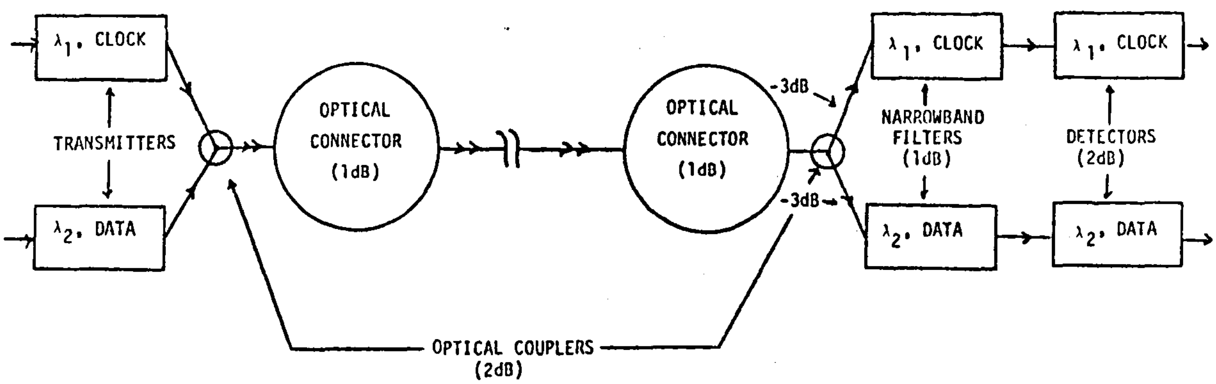


FIGURE 50 LOSSES ASSOCIATED WITH OPTICAL DUPLEXED SYSTEM

A minimum loss of 3.5 → 4.0 dB/km can be expected from cabled optical fibers operating at 830 nm. The section between the LCC and the Pad should contain two splices and three sections--additional 1 dB loss. The optical filter reduces the transmission of the detected wavelength to 80 percent (1 dB) and the blocked wavelength by .01 percent (40 dB). Finally, 5 dB loss is allowed for temperature and time degradation. The average source power from the optical "pigtail" of an ILD is 0 dBm. The receiver sensitivity for an APD at 10^{-8} BER is:

APD sensitivity = 10 log D - 70

where D is the data rate in Mb/s. The receiver sensitivity at 100 Mb/s is:

APD sensitivity = 10 log 100 - 70 = -50 dBm

leaving an excess margin of 0 dB (Figure 51).

The dispersion analysis in this case is used to calculate the maximum allowable data rate. Previous calculations showed the worst case analysis to be within the system requirements, however, in this case, the worst case may unrealistically limit the maximum data rate. There are several ways to calculate the dispersion of an optical link:

1. Sum the risetimes of the components.
2. Take the squre root of the squares of the component risetimes.

$$1.1 \sqrt{t_1^2 + t_2^2 + \ldots t_n^2}$$

3. Use experimental results.

The worst case (1), shown in Figure 52, transmits data at a maximum of 70 Mb/S. The best case (3) results from experimental data which is applicable to long transmission lines, but may not be entirely accurate for this system; nevertheless, experiments have shown for long transmission lines the dispersion can be as low as .5 ns/km, resulting in a maximum data rate of 130 Mb/s. Therefore, a reasonable estimate of the maximum data rate is 100 Mb/s.

	AMOUNT OF LOSS (dB)	FUTURE EXPECTATIONS (dB)
CONNECTOR LOSS (1 dB/CONNECTION)	4	2
OPTICAL COUPLER	7	5
FIBER LOSS (4 dB/Km)	30	23 (3 dB/Km)
SPLICING LOSS (1/2 DB/SPLICE)	1	1
RECEIVER COUPLING LOSS	2	1
OPTICAL FILTER LOSS	1	1
TIME DEGRADATION	3	2
TEMPERATURE DEGRADATION	2	2
TOTAL ATTENUATION	50 dB	37 dB
AVERAGE SOURCE POWER P_S	0 dBm	5 dBm
RECEIVER SENSITIVITY P_R	-50 dBm	-55 dBm
TOTAL MARGIN	-50 dB	-60 dB
EXCESS POWER (TOTAL MARGIN - TOTAL ATTENUATION) =	0 B	23 dB

FIGURE 51 POWER MARGIN ANALYSIS FOR PAYLOAD MONITORING LINK USING ILD/APD AT 10^{-8} BER AND 100 MB/S.

	WORST CASE	BEST CASE	FUTURE EXPECTATIONS
RISETIME OF OPTICAL FIBERS (7.6 Km)	$1 \frac{ns}{Km}$ | 7.6 ns	$.5 \frac{ns}{Km}$ | 3.8 ns	$.25 \frac{ns}{Km}$ | 1.9 ns
RISETIME OF ILD	1 ns	0.7 ns	.5 ns
RISETIME OF APD	1 ns	1.0 ns	.5 ns
TOTAL RISETIME	9.6 ns	5.5 ns	2.9 ns
DATA RATE = $\frac{.7}{\text{TOTAL RISETIME}}$	70 MB/S	130 MB/S	250 MB/S

FIGURE 52 RISETIME ANALYSIS FOR PAYLOAD MONITORING LINK USING ILD/APD AT 10^{-8} BER

4.2.3 Recommendations

For the payload drag-on optical link which has an upper data rate of 300 Mb/s--laser diodes are required. When the actual payload data rate does not exceed 50 Mb/s, as do most near-term payloads surveyed in the mid-term report and all attached payloads, then LEDs can be used. Furthermore, unlike laser diodes and their ancillary circuits and heat sinks. LEDs are small enough to be fitted into a connector, relieving the payload contractor of providing an electro-optical interface. Several multi-channel optical connectors should be available by the end of next year. The payload contractor must still provide proper electrical mating circuits. A PIN diode can be used with either a LED or ILD since the short distance (100→200 m) allows ample power to reach the photodetector and the wide dynamic range of the PIN diode allows it to accept the variations in received power. Furthermore, the PIN diode is fast enough to meet the high data rate requirements. Graded-index fibers with their low dispersion (1 ns/km) or high bandwidth, and moderate loss (5 dB/km) are adequate to meet the requirements for both high data rate and maximum transmitted power.

A list of important parameters is given in Figure 53.

	50 to 300 Mb/s	0 to 50 Mb/s	0 to 300 Mb/s
PARAMETERS	LASER DIODE	LED (BURRUS)	PIN DIODE
COUPLED INPUT POWER	0 dBm (1 mw)	-10 dBm (.1 mw)	
COUPLED OUTPUT POWER AT 300 mB/s, 10^{-8} BER			-30 dBm
WAVELENGTH	820 nm	820 nm	820 nm
RISETIME	1 ns	3 ns	1 ns
SUPPLY VOLTAGE	5 V/200 mA	5 V/100 mA	20 to 50 V/1 mA
TEMPERATURE RANGE	TEMPERATURE CONTROLLED -50°C to +65°C	-40°C to 90°C	-40°C to 70°C
DARK CURRENT			1 to 2 nA
RESPONSIVITY			.55 A/w
COST	$350	$50	$50
COMMERCIALLY AVAILABLE	YES	YES	YES

FIGURE 53 TRANSMITTER/RECEIVER PARAMETERS FOR PAYLOAD CHECKOUT LINK

The data from the payload to the Orbiter/MLP/PAD/LCC must be multiplexed and transmitted to the highest possible data rate. This requires the fastest devices and the lowest dispersion optical fibers: graded-index fibers (1 ns/km). Also, the long distance requires the most powerful/sensitive devices and the lowest loss fibers, which for cabled fibers is 3 to 4 dB/km.

A list of the important parameters is given in Figure 54.

PARAMETERS	LASER DIODE	APD
COUPLED POWER	0 dBm	
COUPLED OUTPUT POWER AT 10^{-8} BER AT 100 mB/s		-50 dBm
RISE TIME	1 ns	1 ns
WAVELENGTHS FOR DUPLEXING	820, 860	APD WITH 10 nm FILTERS CENTERED AT 820/860
LIFETIME	10^5 HRS	10^5 HRS
TEMPERATURE RANGE	TEMPERATURE CONTROLLED -50° to +65°C	TEMPERATURE CONTROLLED -40°C to +70°C
RESPONSIVITY		60 to 70 A/w
DARK CURRENT		10 to 20 nA
SUPPLY VOLTAGE	5 V/200 mA	300 to 355 V/1 mA
COST	$350	$350
COMMERCIALLY AVAILABLE	YES	YES

FIGURE 54

TRANSMITTER/RECEIVER PARAMETERS FOR PAYLOAD MONITORING LINK AT 100 Mb/s

4.3 ELECTRICAL DRIVE CIRCUITS FOR OPTICAL COMPONENTS

Optical components require electrical circuits to drive the sources and detectors to convert the optical signal back to an electrical signal, properly encode the data and aid in the transfer of data from high data rate optical channels into lower data rate channels.

4.3.1 Transmitter/Receiver Circuits

Generally, there are a number of high quality, reliable transmitter/receiver packages which operate in the range of DC to 45 Mb/s which are available as off-the-shelf packages (Figure 55). They can be modified for slightly higher data rates and longer distances. In addition, many manufacturers (IT&T, Harris Corp., Motorola, etc.) have demonstrated their capability for designing, building, and testing transmitters and receivers capable of much higher data rates. However, it is difficult to compare these optical systems against each other or against KSC requirements, since they were built for special applications. Examples of transceiver circuits which do meet the requirements are shown for illustration.

The 50 Mb/s approach for the payload checkout link requires a LED to be inserted into a multipin connector to be directly attached to the payload. Presently, only single-pin optical connectors with LEDs can be bought off-the-shelf, but by the middle of 1981 results from the testing of prototypes will provide insight into the feasibility of a multi-source/multi-pin concept. It remains to be seen if a transmitter circuit can be included within a multipin connector, if not, then a mating circuit must be provided within the payload. Two mating circuits, depending on the distance from LED to drive circuit, are provided in Figure 56.

When payload data rates exceed 50 Mb/s, an injection laser diode and transmitter circuit are required. Since it is extremely doubtful that an ILD with a thermoelectric heater/cooler can be placed inside a connector, an interface must be provided at the test stand or the payload. In either case, Figure 57 shows a transmitter circuit for an ILD built and tested for the MMIFOT Program (JSC NAS9-15585) which is capable of transmitting up to 500 Mb/s. This circuit is capable of meeting the requirements (1 Mb/s to 100 Mb/s) of the payload monitoring link as well.

COMPANY	RECOMMENDED LENGTH	DATA RATE	REMARKS
HEWLETT PACKARD	10-100 m	10 Mb/s	TTL COMPATIBLE LED/PIN SYSTEM
RCA	1 Km	DC TO 20 Mb/s	TTL COMPATIBLE LED/PIN SYSTEM
HARRIS CORP.	>1 Km	10 Kb/s TO 45 Mb/s	TTL COMPATIBLE ILD/APD SYSTEM
SPECTRONICS	2 Km	10 Kb/s TO 10 Mb/s	"SWEET SPOT" LED/ PIN SYSTEM TTL COMPATIBLE
IT&T	2 Km	200 b/s TO 20 Mb/s DC TO 5 Mb/s 20 MHz (ANALOG)	TTL COMPATIBLE LED/PIN SYSTEM

FIGURE 55 TABLE OF TRANSMITTER/RECEIVER PACKAGES

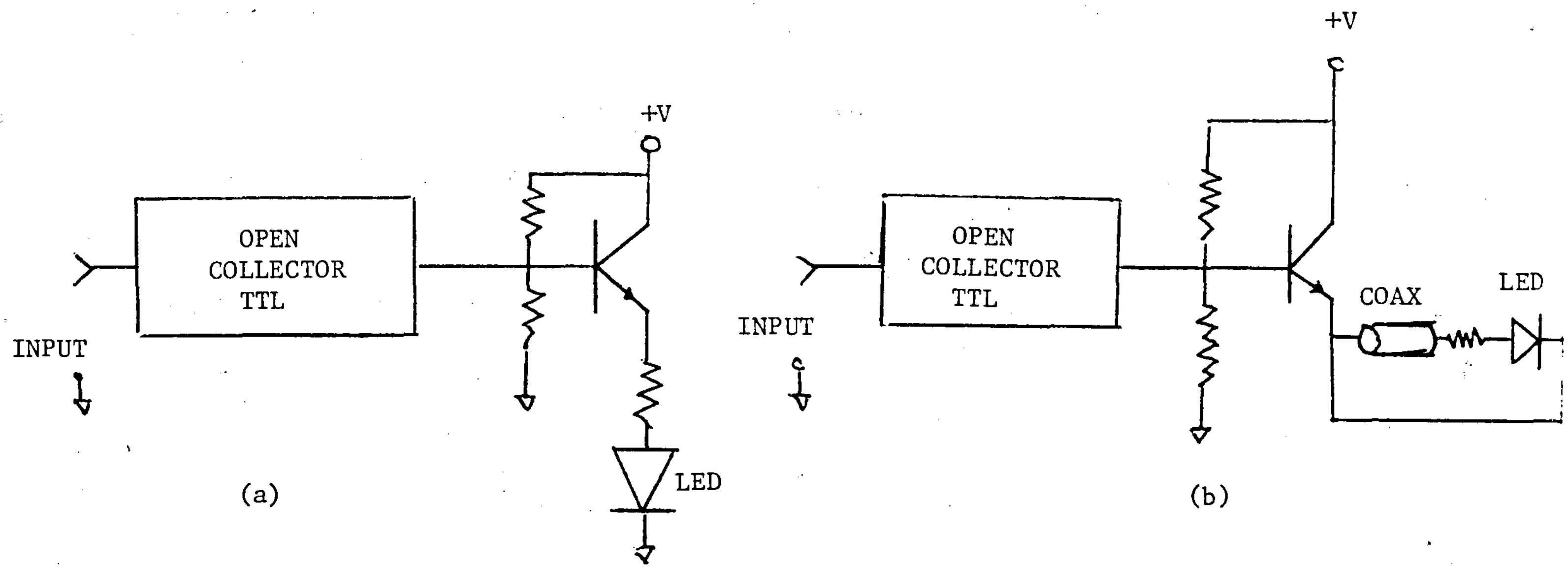


FIGURE 56 (a) LED DRIVER CIRCUIT
(b) LED DRIVER CIRCUIT FOR REMOTELY LOCATED LED

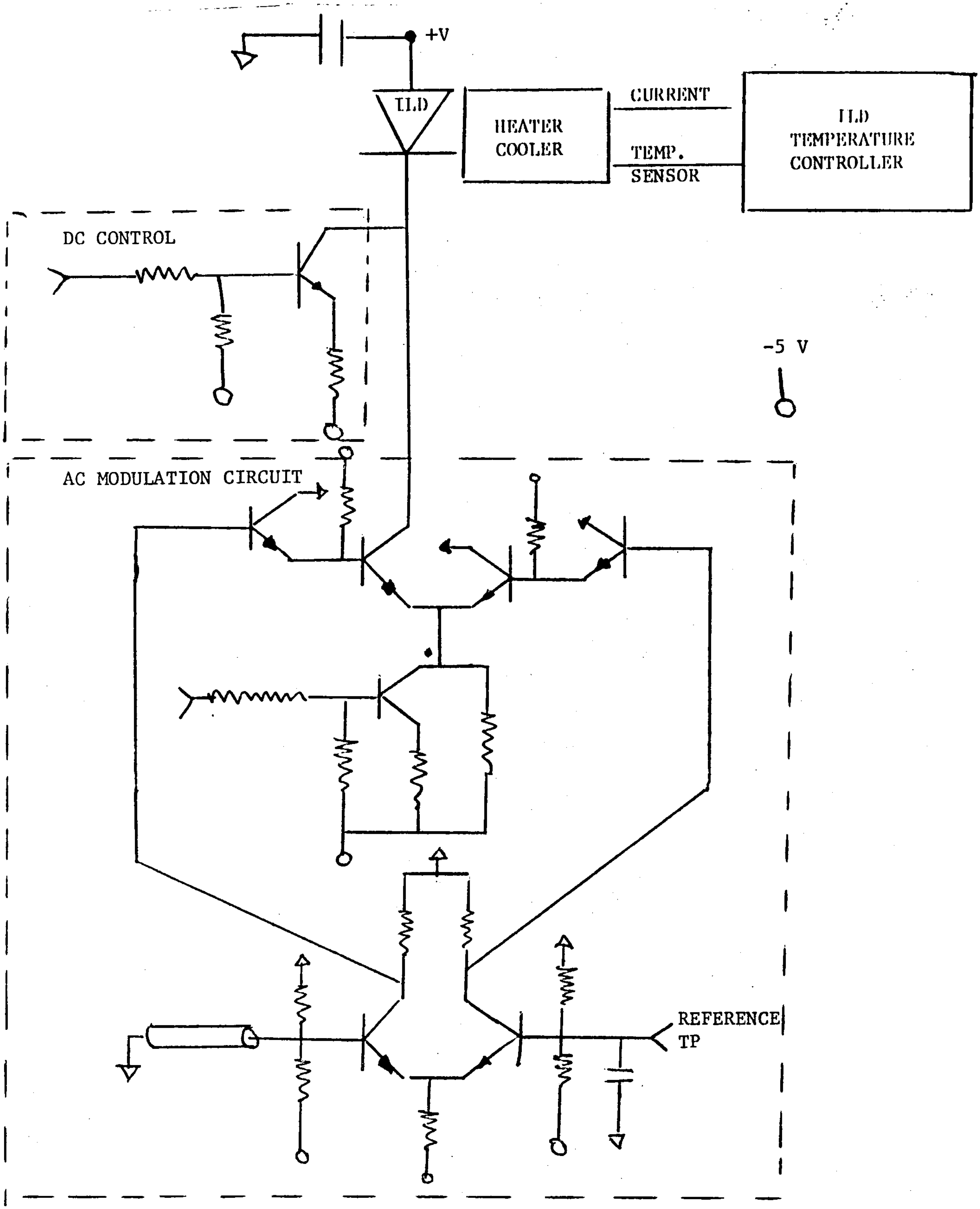


FIGURE 57 ILD TRANSMITTER CIRCUIT FOR DC TO 500 Mb/s DATA RATE

A receiver circuit is principally designed for two purposes: (1) change the signal from the photodetector into a signal compatible with the TTL electronics and (2), ideally, not to add more noise or amplify the noise from the photodetector (shot, thermal and multiplication noise). The preamplifier begins the process of amplifying the signal and consists of either a high impedance integrating FET for low frequencies (<10 MHz) or bipolar preamplifiers with low transimpedances for higher frequencies (>10 MHz). The transimpedance (feedback) is defined as the output voltage divided by the output current from the photodetector and provides an ideal load line for linear operation and good frequency response. The preamplifier is designed to limit noise by having a bandwidth equal to the signal bandwidth and not amplify the noise by having a low impedance. The preamplifier is followed by more amplifiers which flatten the overall signal band pass and bring the signal up to TLL levels.

A receiver circuit for the payload checkout link (Figure 58) should be capable of responding to data rates from 1 Kb/s to 50 Mb/s for the (LED/PIN) system and 50 Mb/s to 300 Mb/s for a ILD/PIN system. Since a PIN diode has a sensitivity of .6A/W and the receiver must respond to power variations of -5 dBm to -20 dBm, the lowest received power multiplied by .6 A/W gives .06 mA into the transimpedance preamplifier. A transimpedance resistance of 1 kΩ provides .06V to the limiting amplifier. A limiting amplifier can be designed to handle 20 dB swings in the light output to the receiver. An automatic gain control (AGC) circuit can provide wider dynamic range but does not appear necessary. A receiver circuit (Figure 59) for the payload monitor link operating in the range of 1 Mb/s to 100 Mb/s uses an APD with a sensitivity of 70 A/W. The power input to the receiver is -45 dBm (.03 μW) without degradation effects. Therefore, an input of 2.1 μA into the preamplifier with a 1 kΩ transimpedance becomes 2.1 mV at the output. The limiting amplifier converts the voltage to TTL voltage requirements. Finally, an optical signal monitor (OSM) should be connected to the receiver circuit to measure voltage levels from the preamplifier which go below .7 mV (-50 dBm). The OSM circuit performs the function of indicating when the BER requirement is not being met.

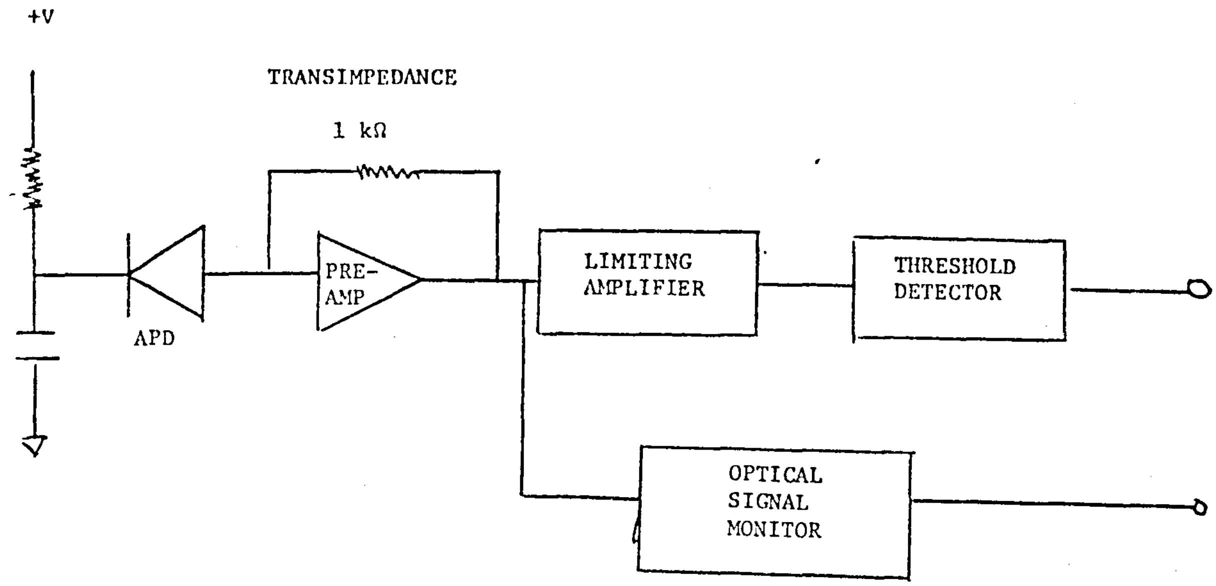


FIGURE 58 RECEIVER CIRCUIT FOR PAYLOAD CHECKOUT LINK

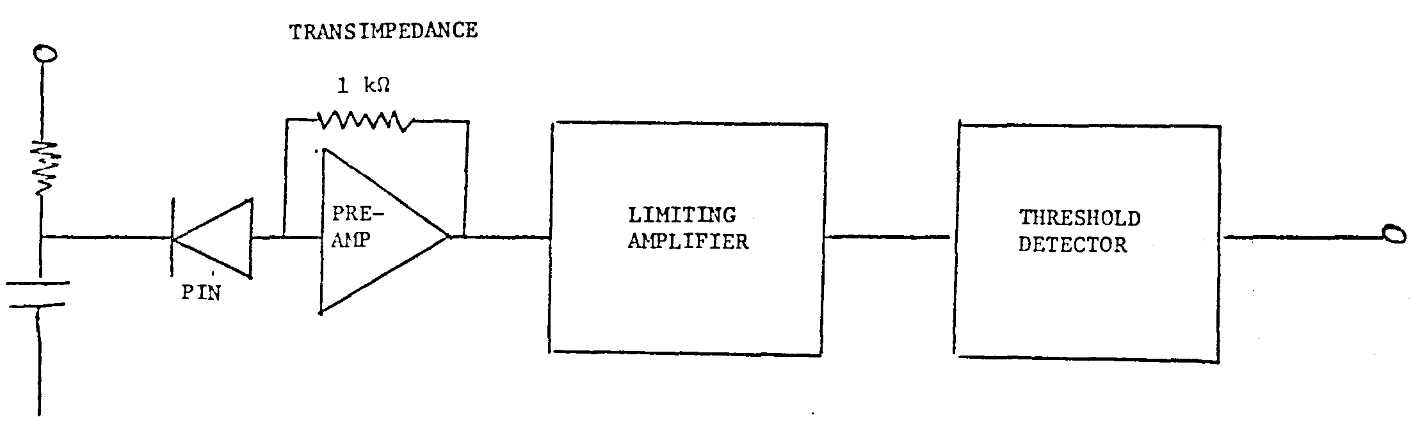


FIGURE 59 RECEIVER CIRCUIT FOR PAYLOAD MONITOR LINK

4.3.2 Conversion of Manchester Data Format to NRZ Format

For both the payload checkout link and the payload monitor link, a NRZ format is used to transfer the highest possible data rate. However, the input/output data format is Manchester coded; therefore, an electrical circuit must be used to change the data format. A block diagram (Figure 60) shows the conversion of Manchester to NRZ coded data and another block diagram (Figure 61) shows the conversion of NRZ to Manchester coded data. For the payload checkout link, the payload contractor may simply supply the NRZ coded data. But for the payload monitoring link, the Orbiter already is designed to transmit Manchester II coded data and, therefore, must be converted to NRZ coded data for transmission.

4.3.3 Transmission of the Maximum Payload Data Rate

As shown in Section 4.2.1, there is no difficulty in transmitting the maximum payload data of 300 Mb/s over short distances (<200 m). For transmission over longer distances, for example from the VPF to the OCC, which is slightly over 2 km or from the CD&SC to the PPF which is several kilometers, it may not be possible or economical to transmit 300 Mb/s with existing optical components. Therefore, in order for the payload data to reach remotely located GSE equipment, high data rate channels are subdivided into lower data rate channels and then recombined at the other end. Figure 62 shows a block diagram of how a 50 to 300 Mb/s channel can be transmitted over one to six channels rated, for example, at 50 Mb/s. The clock is sent on a separate channel. Information is initially sent to both the transmitter and receivers providing the number of lines transmitting and receiving information. Then a single data channel enters a shift register and loaded into one six parallel lines. At the receiver end, the data enters load registers and is alternately transferred to two shift registers. The data is recombined together by a multiplexer into a single channel. The clock is regenerated by a circuit having two VCOs operating in the range of 50 to 150 Mb/s and 150 Mb/s to 300 Mb/s. A multiplexer selects the appropriate range based on previous information. The circuit decreases in complexity as the data capacity of the KSC land lines increases, by removing one of the VCOs.

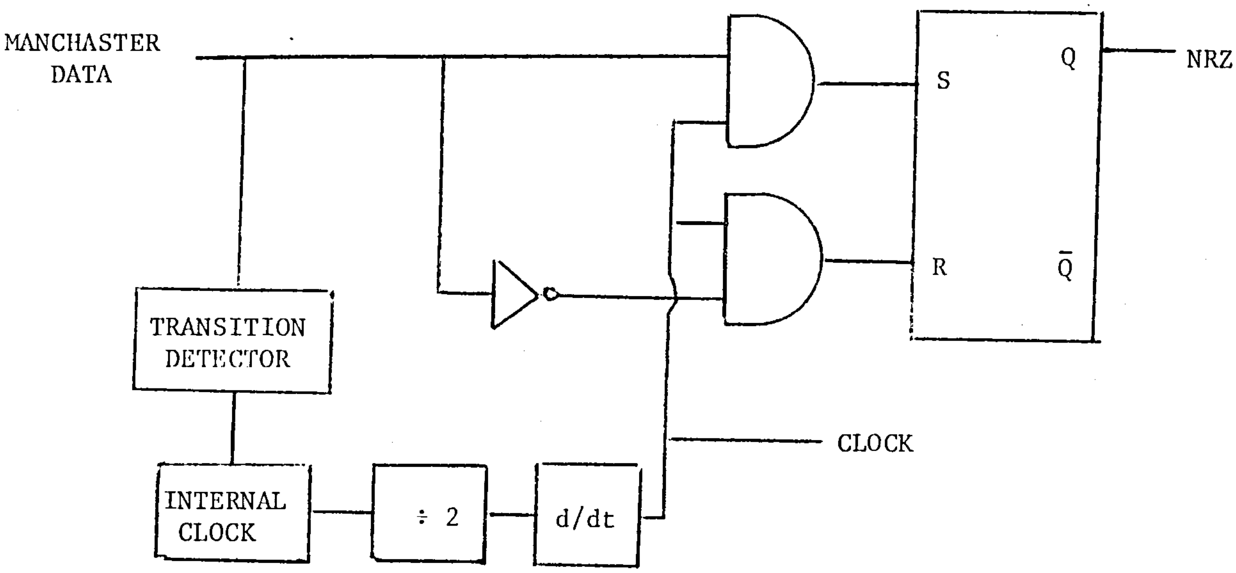


FIGURE 60 CONVERSION OF MANCHESTER DATA TO NRZ DATA

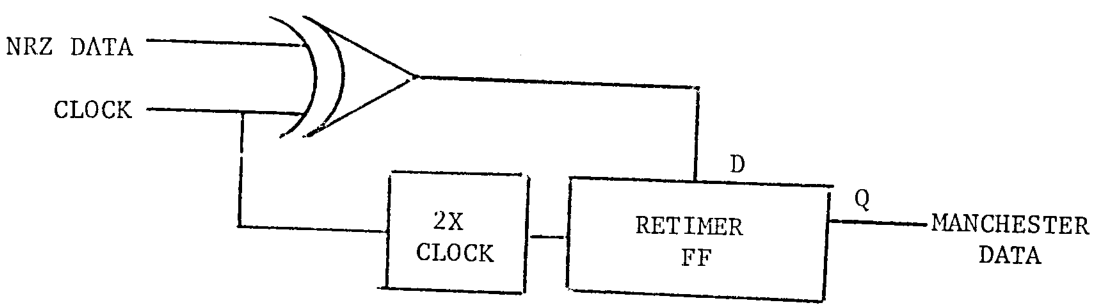


FIGURE 61 CONVERSION OF NRZ DATA TO MANCHESTER DATA

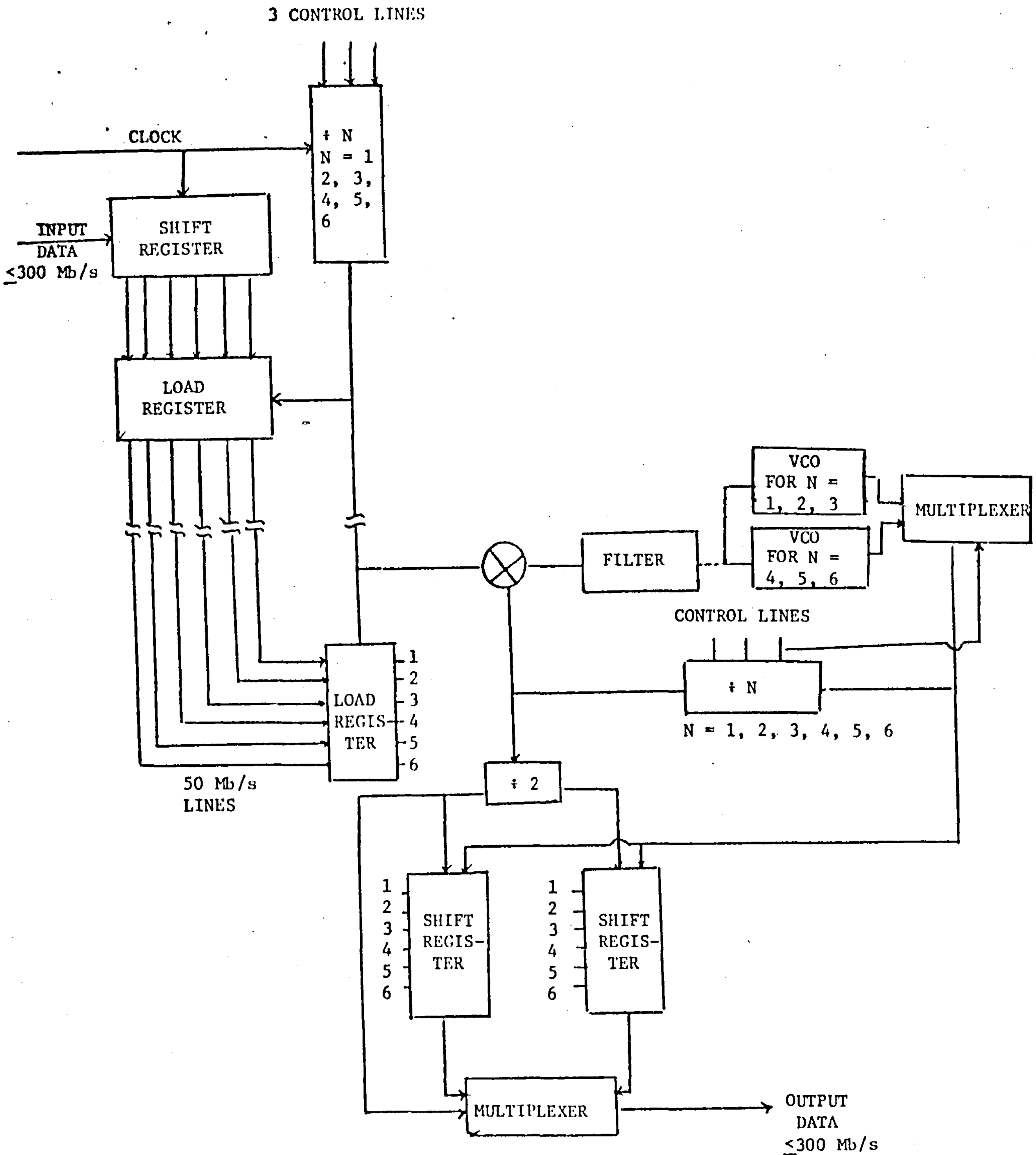


FIGURE 62 A CIRCUIT FOR TRANSMITTING 300 Mb/s (OR LESS) OVER 50 Mb/s OPTICAL CHANNELS

4.4 QUANTITATIVE COMPARISON OF MULTIPLEXING TECHNIQUES

Using the information developed in the previous sections, a comparison can now be made between the present electrical communication system using no multiplexing techniques, an optical communication system using an efficient time division multiplexing technique (bit-stuffing/resynchronization), an optical communication system using an inefficient time division multiplexing technique (oversampling), and a future optical wavelength division/time division multiplexing scheme using packet telemetry. The purpose of this comparison is to show the major reduction in data channels (electrical wires) when high data capacity optical channels are employed. The payload monitor link was chosen because of its well-defined data channels, as opposed to the payload checkout link which requires knowledge of individual payloads. The data channels for the payload monitoring link are the same as for the T/O cables which carry a combination of payload and Orbiter data. These data channels, described in the Payload/Orbiter/MLP Interface Document (ICD-2-0A002), are listed in columns one through three of Figures 63 and 64 for both cables (01-02), and represent the present electrical communication system. To compare the two time multiplexed systems, it is necessary to establish some ground rules for multiplexing:

(1) A maximum allowable data rate (NRZ) of 100 Mb/s per optical fiber (Section 4.2.2).

(2) PCM channels which are to be resynchronized or bit-stuffed are multiplexed at their maximum data rate.

(3) Oversampling is sampled at ten times the maximum data rate.

(4) Double-layered multiplexing is shown in enclosing two data rates.

(5) For the PSK channel, the subcarrier is blocked and the 10 Kb/s data is multiplexed with the low data rate channels.

(6) All analog channels are converted to PCM by sampling at 2.5 times the maximum frequency and having 6 bits/sample; 4 to 6 bits/sample provides for adequate signal fidelity and 6-8 bits/sample provides for excellent signal fidelity

(7) All analog channels are multiplexed the same way for all time multiplexing methods.

(8) The 4.608 MHz sinewave is converted to 4.608 Mb/s.

Summing the channels for the two-time multiplexed systems gives a total of 13 optical fibers for bit-stuffing/resynchronization and 15 optical fibers for oversampling, as contrasted to 120 electrical wires for the present communication system. The small difference in the total number of optical fibers results from: (1) the large number of analog channels in proportion to the total number of channels, since they are multiplexed in a similar manner for both systems, and (2) the high data capacity of the optical fibers. Further reduction in optical fibers (5) can be accomplished in a future optical communication system by wavelength multiplexing several time multiplexed channels through a single optical fiber. This may reduce the number of optical fibers or allow for future growth using the present projected number of optical fibers (15).

In conclusion, oversampling asychronous digital channels would allow for the least expensive method of reducing the number of channels transmitted. As data requirements grow, a wave/time multiplexed system, using packet telemetry, could be implemented.

CHANNEL OUTPUT	DATA RATE BANDWIDTH (MAX)	TYPE	MULTIPLEXING BY BIT-STUFFING AND RESYNCHRONIZATION	MULTIPLEXING BY OVERSAMPLING 10 TIMES MAXIMUM FREQUENCY	FUTURE OPTICAL SYSTEM USING 5 CHANNEL MULTIPLEXER
1	256 Kb/s	PCM/DIGITAL			
2	60 Kb/s	PCM/DIGITAL			
3	60 Kb/s	PCM/DIGITAL			
4	64 Kb/s	PCM/DIGITAL			
5	128 Kb/s	PCM/DIGITAL		23.1 Mb/s	
6	16 Kb/s	PCM/DIGITAL			
7	2 Kb/s	PCM/DIGITAL		COMBINED INTO ONE CHANNEL	
8	60 Kb/s	PSK/1024 KHz	16 Mb/s		
9	60 Kb/s	SCO/576/768/1026 KHz			
10	1024 Kb/s	PCM/DIGITAL		51.2 Mb/s	
11	1000 Kb/s	PCM/DIGITAL			
12	1024 Kb/s	PCM/DIGITAL			
13	1024 Kb/s	PCM/DIGITAL			
14	1024 Kb/s	PCM/DIGITAL			
15	4.608 MHz	SINEWAVE			
16	5 Mb/s	PCM/DIGITAL		100 Mb/s	

FIGURE 63 SUMMARY OF MAXIMUM DATA RATES THROUGH THE 0-1 T/O AND EXPECTED DATA RATES FROM MULTIPLEXING

CHANNEL OUTPUT	DATA RATE BANDWIDTH (MAX)	TYPE	MULTIPLEXING BY BIT-STUFFING AND RESYNCHRONIZATION	MULTIPLEXING BY OVERSAMPLING 10 TIMES MAXIMUM FREQUENCY	FUTURE OPTICAL SYSTEM USING 5 CHANNEL MULTIPLEXER
17	3 KHz	ANALOG	97.2 Mb/s	97.2 Mb/s	75, 100, 97.2,
18-43	240 KHz	ANALOG			93 AND 82 Mb/s
44-50	240 KHz	ANALOG	* 25.2 Mb/s	93 Mb/s	COMBINED INTO
51	4.5 MHz	ANALOG (TV)	67.7 Mb/s		ONE FIBER
52-57	240 KHz	ANALOG	** 21.6 Mb/s	82 Mb/s	
58	4 MHz	ANALOG	60 Mb/s		
INPUT					
1	16 Kb/s	PCM/DIGITAL	1.1 Mb/s	30 Mb/s	30 Mb/s
2	3 KHz	ANALOG			
3	1 Mb/s	PCM/DIGITAL			
TOTAL MULTIPLEXED CHANNELS			5	6	2

* COMBINED INTO SINGLE 93 Mb/s CHANNEL

**COMBINED INTO SINGLE 82 Mb/s CHANNEL

FIGURE 63 SUMMARY OF MAXIMUM DATA RATES THROUGH THE O-1 T/O AND EXPECTED DATA RATES FROM MULTIPLEXING CONT.

CHANNEL OUTPUT	DATA RATE BANDWIDTH (MAX)	TYPE	MULTIPLEXING BY BIT STUFFING AND RESYNCHRONIZATION	MULTIPLEXING BY OVERSAMPLING 10 TIMES MAXIMUM FREQUENCY	FUTURE OPTICAL SYSTEM USING 4 CHANNEL MULTIPLEXER
1	128 Kb/s	PCM/DIGITAL			
2	128 Kb/s	PCM/DIGITAL			
3	60 Kb/s	PCM/DIGITAL			
4	128 Kb/s	PCM/DIGITAL	2.1 Mb/s	70 Mb/s	
5	64 Kb/s	PCM/DIGITAL			70, 97.2, 61.2, AND 60 Mb/s COMBINED INTO ONE FIBER
6	576 Kb/s	PCM/DIGITAL			
7	1000 Kb/s	PCM/DIGITAL			
8	3 KHz	ANALOG	97.2 Mb/s	97.2 Mb/s	
9-34	240 KHz	ANALOG			
35-51	240 KHz	ANALOG	61.2 Mb/s	61.2 Mb/s	

FIGURE 64 SUMMARY OF MAXIMUM DATA RATES THROUGH THE 0-2 T/O AND EXPECTED DATA RATES FROM MULTIPLEXING

CHANNEL OUTPUT	DATA RATE BANDWIDTH (MAX)	TYPE	MULTIPLEXING BY BIT-STUFFING AND RESYNCHRONIZATION	MULTIPLEXING BY OVERSAMPLING 10 TIMES MAXIMUM FREQUENCY	FUTURE OPTICAL SYSTEM USING 4 CHANNEL MULTIPLEXER
52-53	2 MHz/1024 Kb/s	ANALOG	60 Mb/s	60 Mb/s	
54-56	2 MHz/1024 Kb/s	ANALOG	90 Mb/s	90 Mb/s	90, 90, 90,
57-59	2 MHz/1024 Kb/s	ANALOG	90 Mb/s	90 Mb/s	90 Mb/s
60-62	2 MHz/1024 Kb/s	ANALOG	90 Mb/s	90 Mb/s	COMBINED INTO
63-65	2 MHz/1024 Kb/s	ANALOG	90 Mb/s	90 Mb/s	ONE FIBER
INPUT					
1	3 KHz	ANALOG			
2	216 Kb/s	PCM/DIGITAL	1.261 Mb/s	30 Mb/s	30 Mb/s
3	1 Mb/s	PCM/DIGITAL			
TOTAL MULTIPLEXED CHANNELS			8	9	3

FIGURE 64 SUMMARY OF MAXIMUM DATA RATES THROUGH THE O-2 T/O AND EXPECTED DATA RATES FROM MULTIPLEXING CONT.

5.0 COMPARISON OF PRESENT ELECTRICAL APPROACH WITH OPTICAL APPROACHES

The Introduction listed a number of advantages of optical transmission over electrical transmission methods without identifying which advantages are important for payload data transmission. For the purposes of this comparison, the payload data passes through three unique transmission links: landlines connecting PAD to LCC; cables connecting PAD to MLP to Orbiter; and umbilical cables connecting the payload to the GSE equipment. The comparison between optical and electrical transmission (Figure 65) is made on the basis of the growth capacity of the hardware, distribution of singals, weight/size of cables, amount of EMI protection and equipment costs. Since the transmission links are not fully defined, only general statements about component reliability, maintainability, and personnel impact are made.

The communication transmission hardware of KSC must grow in its capacity to meet the demands of frequent Orbiter launches and the ultimate transmitting capacity of payloads. Already "bottlenecks" are developing between distribution centers such as the VABR, LCC, CD&CS, and O&C buildings. There are three solutions which meet existing demands and future growth. The first solution is time sharing existing transmission lines. While this method has proved cost-effective for the present, it may prove inconvenient in the future. For example, payloads may require additional checkout when problems are discovered; assigning priorities may prove difficult when all subsystems must be operational before launch; time-sharing may become overburdened when the payload data rate reaches its upper maximum (300 Mb/s) and must be subdivided through low data rate transmission lines. Moreover, since the Orbiter launches are considered "success oriented," time sharing may not allow the flexibility to solve problems quickly and without delays. A second, more expensive solution is to expand the existing ducts and lay new electrical cable.

A third solution uses an optical transmission system which would eliminate time-sharing, use the existing ducts, and easily accommodate future growth. Presently, optical channels used for this application (long distance) could handle between 50→100 Mb/s data rates. For example, the landlines between the PAD and LCC carrying payload/Orbiter data were found to be far more effi-

efficient when using optical channels - 60 channels reduced to 10 channels or less. In another example, up to 300 Mb/s must be transmitted from the VPF to the O&C. It is more efficient to transmit and subdivide 300 Mb/s into six optical fibers operating at 50 Mb/s than 60 electrical wires operating at 5 Mb/s. In the first example, the low bandwidth, larger electrical cables (3" diameter/ 36 TSP) could be replaced with high bandwidth, smaller optical cables (.5"/10 fiber). The small size of the optical cables is due in part to the high bandwidth/channel and lack of EMI protection; additional reduction in size results when the optical cable is not pressurized. Modern optical cables can be constructed to prevent water sweepage without pressurization. The final area of comparison is the distribution of signals within KSC. Presently, the entire method of distribution of signals within the NASA communication network is undergoing study and revision. The NASA End-to-End Data System proposes using "packets" of data addressed to their final destination. Such a system would favor a high data rate, time-multiplexed optical data bus over a low data rate, single channel, direct connection between input to output, electrical transmission system by providing for a more timely transfer of information and using the high data capacity optical channels more efficiently (80%).

Cables interconnecting the Orbiter to the MLP and the MLP to the PAD do not have the same environmental requirements as the landlines. For example, protection against rodent damage and water absorption are not problems. Like the landlines, these optical cables would not need EMI protection even against lightning upsets. Therefore, using the same number of optical channels (10 or less) as the KSC landlines between the LCC and the PAD, these optical cables should be slightly larger in diameter than a pencil and have only one optical connector at each end. In contrast, the presently conceived electrical cable would have over 60 electrical channels, five electrical connectors, and have a diameter of over 4".

Payload umbilicals need to be able to transmit up to 300 Mb/s over a distance of 200 m. To meet these requirements an electrical communication system would be difficult to design and expensive to construct.

As been shown in a previous progress report, an optical communication system can be designed to handle data rates up to the maximum limit without difficulty. As before, an optical cable designed for this application would be about the diameter of a pencil and much lighter than its electrical counterpart. The lighter weight results in part from the elimination of EMI protection. Electromagnetic radiation is neither emitted by the optical signal nor is the optical signal interfered with the EMI. Furthermore, optical cables may be laid across electrical power cables without concern, or electrical power lines may be directly combined with optical fibers in a single cable. In conclusion, all three applications of optical communication show advantages over electrical communication in terms of data rate, distribution of signals (NEEDS), weight and size of optical cable.

Better information on reliability and better designs for maintainability of electro-optical systems has been of major effort of manufacturers in the late 1970s. For the 1980-1985 time frame, it can be expected that optical components will have a lifetime of over 10^5 hours (10 years). Maintainability of optical communications requires locating the malfunctioning component and replacing/repairing the component with minimum down time. To locate the malfunction of a number of different types of monitoring circuits have been designed and used. An Optical Power Monitor (OPM) is used to monitor the level of the laser output. An Optical Signal Monitor (OSM) indicates if there is a major reduction in light output from the optical cable. An Optical Signal Quality Monitor (OSQM) can be used to measure the output of the photodector to determine if the BER has been exceeded. Also, optical ohm-meters have been constructed to determine the relative change of attenuation of the optical cables. Finally, with fewer interconnections personnel will find locating malfunctions quicker and easier. For years, maintaining clean optical fiber ends required careful handling, potentially personnel could forget that dust in the optical connector could reduce performance. To eliminate extra careful handling, optical connectors are being constructed with retractable optical fibers and caps with screw on after demating. Today, optical communication systems can be assembled with reliable, discreet components and built-in trouble shooting monitors.

In conclusion, the communication system envisioned for the payload checkout link and the in-place communication system for the payload monitoring link appear to be adequate for the next couple years; although, some payloads with high data rates (Spacelab) and some "bottlenecks" between communication centers are posing immediate problems and being solved by optical data handling methods. But neither conventional communication system will effectively handle the anticipated future growth in data communications at KSC after the first Orbiter launching. As shown in this study, the proposed optical data handling system for both the payload checkout link and the payload monitoring link can easily handle all future growth without any modification of existing ducts. The proposed system is also responsive to changes in the existing data format (NEEDS), reduces the EMI environment and reduces the size/weight of transmission cables. Further, it is believed, although this study does not present sufficient justification, that a thorough cost study of additions and modifications of the present communication system, meeting all future requirements, versus the proposed optical communication system will result in a favorable cost incentive. Finally, compatibility with payloads and the Orbiter should be a future advantage as these systems are studied as applications of optical communications.

	APPLICATION	PRESENT ELECTRICAL TRANSMISSION SYSTEM	PRESENT OPTICAL TRANSMISSION SYSTEM (1980-1985)	FUTURE OPTICAL TRANSMISSION SYSTEM (1985-2000)
GROWTH CAPACITY OF THE TRANSMISSION SYSTEM	PAYLOAD UMBILICALS	DIFFICULT TO TRANSMIT OVER 50 Mb/s TO CONTROL ROOMS.	OPTICAL FIBERS CAN EASILY TRANSMIT UP TO 300 Mb/s.	OPTICAL MULTIPLEXING CAN MULTIPLY THE DATA RATE PER CHANNEL BY 4-8 TIMES.
	T/O CABLES	OVER 60 LOW DATA RATE CHANNELS/CABLE.	OPTICAL FIBERS CAN TRANSMIT 100 Mb/s. 10 OPTICAL FIBERS COULD HANDLE FUTURE GROWTH.	OPEN AIR LASER SYSTEM COULD WORK IN THE GBIT/S RANGE PER CHANNEL.
	KSC LANDLINES	BOTTLENECKS ARE DEVELOPING. TIME SHARING REQUIRED. LITTLE ROOM FOR GROWTH IN THE DUCTS.		
DISTRIBUTION OF SIGNALS	PAYLOAD UMBILICALS T/O CABLES KSC LANDLINES	SOME FREQUENCY MULTIPLEXING. MOST CHANNELS ARE CONNECTED INPUT TO OUTPUT.	EXTENSIVE USE MADE OF MULTIPLEXING. OPTICAL COUPLERS (T-COUPLER, STAR COUPLER) CAN BE USED FOR DISTRIBUTION.	OPTICAL COMPONENTS SUCH AS OPTICAL MULTIPLEXERS AND OPTICAL SWITCHES WILL BE USED IN DISTRIBUTION. PACKET TELEMETRY WILL BE USED IN A DATA BUS SYSTEM.

FIGURE 65 COMPARISON OF PRESENT ELECTRICAL COMMUNICATION SYSTEMS AT KSC WITH FUTURE OPTICAL COMMUNICATION SYSTEMS

	APPLICATION	PRESENT ELECTRICAL TRANSMISSION SYSTEM	PRESENT OPTICAL TRANSMISSION SYSTEM (1980-1985)	FUTURE OPTICAL TRANSMISSION SYSTEM (1985-2000)
WEIGHT SIZE	PAYLOAD UMBILICALS	REQUIRES EMI PROTECTION.	NO EMI PROTECTION.	FEWER FIBERS DUE TO OPTICAL MULTIPLEXING.
	T/O CABLES	DUE TO LOW DATA RATES MORE ELECTRICAL WIRES REQUIRED TO TRANSMIT SAME AMOUNT OF INFORMATION. CABLES HAVE SEVERAL CONNECTORS.	CABLES NEED ONLY ONE CONNECTOR AT EACH END. FEWER CHANNELS RESULTS FROM MULTIPLEXING.	
	KSC LANDLINES	WIRES MADE OF COOPER.		
EMI PROTECTION	PAYLOAD UMBILICALS	EMI PROTECTION IS NECESSARY ON ALL ELECTRICAL CABLES	NO EMI PROTECTION NECESSARY.	NO EMI PROTECTION NECESSARY.
	T/O CABLES KSC LANDLINES		MAY BE LAID DIRECTLY OVER ELECTRICAL POWER LINES. OPTICAL FIBERS AND ELECTRICAL WIRES MAY BE INCLUDED IN THE SAME CABLE.	MAY BE LAID DIRECTLY OVER ELECTRICAL POWER LINES. OPTICAL FIBERS AND ELECTRICAL WIRES MAY BE INCLUDED IN THE SAME CABLE.

FIGURE 65 COMPARISON OF PRESENT ELECTRICAL COMMUNICATION SYSTEMS AT KSC WITH FUTURE OPTICAL COMMUNICATIONS SYSTEMS CONT.

	APPLICATION	PRESENT ELECTRICAL TRANSMISSION SYSTEM	PRESENT OPTICAL TRANSMISSION SYSTEM (1980-1985)	FUTURE OPTICAL TRANSMISSION SYSTEM (1985-2000)
EQUIPMENT COSTS	PAYLOAD UMBILICALS	INDIVIDUAL ELECTRICAL CABLES REQUIRED FOR EACH PAYLOAD.	ADDITIONAL COMPONENT COSTS 200 M CABLES $200/FIBER OPTICAL CONNECTOR $200/PAIR TRANSMITTER/RECEIVER $200/PAIR	OPTICAL MULTIPLEXER WHICH ELIMINATES OPTICAL COMPLEXERS REDUCES OPTICAL FIBERS.
	T/O CABLES	IN PLACE EQUIPMENT	OPTICAL COUPLER $100/ COUPLER OPTICAL FILTER $100/ FILTER OPTICAL FIBER $7.6K/ FIBER (BASED ON $1.00/ M PER FIBER	OPTICAL FIBERS $.50/M PER FIBER TRANSMITTER/RECEIVER $50/PAIR
	KSC LANDLINES	IN PLACE EQUIPMENT	OPTICAL CONNECTOR $100/PAIR TRANSMITTER/RECEIVER $800/PAIR	OPITCAL CONNECTOR $50/PAIR

FIGURE 65 COMPARISON OF PRESENT ELECTRICAL COMMUNICATION SYSTEMS AT KSC WITH FUTURE OPTICAL COMMUNICATION SYSTEMS CONT.

	APPLICATION	PRESENT ELECTRICAL TRANSMISSION SYSTEM	PRESENT OPTICAL TRANSMISSION SYSTEM (1980-1985)	FUTURE OPTICAL TRANSMISSION SYSTEM (1985-2000)
RELIABILITY LIFETIME MAINTAINABILITY	PAYLOAD UMBILICALS T/O CABLES KSC LANDLINES	USES COMPONENTS WITH KNOWN RELIABILITY AND DEVELOPED METHODS OF MAINTAINABILITY.	LIFETIME OF OPTICAL COMPONENTS WILL BE OVER 10^5 HRS (10 YEARS) MAINTAINABILITY - OPTICAL MONITORING TECHNIQUES AVAILABLE. STANDARDIZATION JUST STARTING. TEST EQUIPMENT BEING DEVELOPED. OPTICAL OHM-METER AVAILABLE.	LIFETIME OF OPTICAL COMPONENTS WILL APPROACH 10^6 HRS. STANDARDIZATION COMPLETE. FULLY DEVELOPED TEST INSTRUMENTS.

FIGURE 65 COMPARISON OF PRESENT ELECTRICAL COMMUNICATION SYSTEMS AT KSC WITH FUTURE OPTICAL COMMUNICATION SYSTEMS CONT.

6.0 TASK E--FOLLOW-ON ACTIVITY

This study proposes near-term options with external electro-optical interfaces to the payload and Orbiter, and long-term options with internal electro-optical interfaces to the payload and Orbiter. The near-term options are designed to accept whatever data rate and format is transmitted by either the payload or the Orbiter, since design and hardware changes in the immediate future are not considered possible. The long-term options assume hardware can be changed, eliminating interface problems such as asynchronous channels and signal compatibility. It is recommended that the follow-on activity pursue options B and C for the payload checkout link and options C and D for the payload monitoring link.

6.1 PAYLOAD CHECKOUT LINK

Payloads carried by the Orbiter and launched by KSC will be built by a variety of payload contractors; therefore, a common optical link with electro-optical interfaces internal to the payload and the ground support equipment (GSE) must be able to accommodate a number of different payload requirements and designs. The purpose of this study is to identify and reduce interfacing problems between the optical link and the payload at one end and the GSE equipment at the other end. Once a common optical link is designed and put in place, payload contractors would be required to design their payloads and GSE equipments to interface with it. Therefore, it is important for maximum utilization of the optical payload checkout link that the payload contractor's comments on the specifications be obtained before it is designed and fabricated.

TASK A	Prepare Study
TASK B	Compile Results from Survey and Identify Problem Areas
TASK C	Recommend Solutions
TASK D	Select Components for Final Design
TASK E	Follow-On Activity

A letter is prepared in Task A composed of an explanation of the purpose of the study, a description of the proposed optical link, and a list of questions. The questions would be directed towards the following topics: identifying interfacing problems, a convenient time frame for introducing optical communications, the number of channels that should be made available, anticipated

additional cost to the payload contractor and any unforeseen disadvantages. The letter will be first sent to KSC for approval and then sent to all the major payload contractors to avoid biasing results or overlooking problems. Task B compiles comments and results according to the problem areas. Trade studies are performed in Task C and solutions to the problem areas are recommended. Task D states the specifications based on Task B and Task C and then selects electrical and optical components for the final design. Task E concludes with any follow-on recommendations. The entire study is estimated to take 9 to 12 months depending on how quickly the responses from the major contractors are returned.

6.2 PAYLOAD MONITORING LINK

There would be little advantage for payloads to optically interface with the Orbiter or for the T/O cables to be converted to optical cables unless the Orbiter itself was redesigned with an optical data bus. Therefore, a study to compare the present internal Orbiter communication system with an optical data bus communication system designed for the Orbiter should be presently undertaken. The study consists of the following tasks:

TASK A	Study Present Orbiter Communication System
TASK B	Design a Multiplexed Data Bus System Using Optical Fibers
TASK C	Compare the Two Communication Systems
TASK D	Select a Noncritical Communication Link Within the Orbiter
TASK E	Follow-On Activity

Task A would consist of gathering all relevant data regarding the present Orbiter communication system requirements, both internal to the Orbiter and external to the Orbiter (interfacing with payloads and KSC ground support equipment). Once all the documents had been collected and studied, work would begin designing a data bus communication system using optical data handling methods. Task C would compare the two communication systems, following the same procedure as in this report. If the study convincingly shows advantages of employing an optical data bus, then a noncritical communication link within the Orbiter should be chosen for testing (Task D). For Task E, redundant optical data link could be put through a series of launches to test its performance during launch, in space, and after landing. Optical components could

be interchanged for comparison or remain through several launches to test for reliability and lifetime. Since the testing phase could require a few years of testing and evaluating the results, the study phase should begin as soon as possible. The Navy Aloft Program, an optical data link for a Navy fighter aircraft, had much success following a similar procedure.

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15. Abstract

Vol 1 Executive Summary
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The objective of the study is to determine the feasibility of using optical data handling methods to transmit payload data. Ground check-out data requirements are classified into two categories: One - Data rates up to 70 MBPS for distances up to 7.2 KM and data up to 300 MBPS for distances up to 200 M, an optical approach is selected for each category and Data multiplexing techniques is addressed. Component selection is made based on the performance parameters of LED's, and semi-conductor lasers, optical fibers both single-mode and multi-mode and photo detectors both pin diodes and avalanche photo-detectors. A quantitative analysis of the rise time (dispersion) and power margin (attenuation) is used to select optical components. The report concludes with a comparison of the conventional electrical communication system to the proposed optical communication system.

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